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RADIUM THERAPY

RADIUM THERAPY

Its Physical Aspects

By

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PREFACE

For some time I have felt that a book dealing with the physical aspects of radium therapy, particularly the most recent developments, would be welcomed by workers engaged in this branch of radio-therapy and would also be of interest to others wishing to learn something of the application of physics to this subject. Because of the wider and more planned application of radiotherapy that is to be expected in the near future as a result of the implementation of the Cancer Act of 1939, possibly along the lines suggested in the recent memoranda published by the National Radium Commission and the Faculty of Radiologists, this feeling has become a conviction. The following pages represent my attempt to write such a book.

It has been my earnest endeavour to produce a book which, at least as regards certain sections, will be of value and interest to all the different types of workers in radio-therapy as well as to physicists. From the beginning of radium therapy it has been the concern of the physicist to study methods for the measurement and control of gamma ray dose and dose distribution, and his success in this respect has played no little part in the progress of this form of therapy. It is my hope that this book will help to make this work of the physicist appear (particularly to those who are not physicists) as a more co-ordinated whole than hitherto, so that in our future co-operation we may understand one another better than before.

In order to concentrate attention upon the most recent developments, which form the basis of present-day methods, I have deliberately restricted the bibliography and have referred chiefly to work published during the last twelve or fifteen years. Wider reference to the considerable body of literature on the subject may be made quite easily through the bibliographies given in the work to which I have referred. Again, it may appear that certain matters, as for instance the basic ideas behind the technique of cross-fire, etc., in teletherapy, have received too little consideration. My reason for the attitude I have taken in these cases is that these matters have already been dealt with most adequately in a number of other excellent books well known to workers in the field of radio-therapy.

Many of the illustrations and tables have been reproduced directly or indirectly from the published works of various authors. The source of these is usually acknowledged in the text, but I should like to thank all these authors, and any others whom I may have overlooked, for their kind permission to reproduce these illustrations.

I am also indebted to the Editors of the *British Journal of Radiology*, *Acta Radiologica*, the *American Journal of Roentgenology and Radium Therapy* and the *Proceedings of the Physical Society*, and to H.M. Stationery Office and the Department of Health, Commonwealth of Australia, for permission to use certain illustrations and tables also acknowledged in the text. Some other illustrations have been reproduced by permission of Messrs. John Wright & Sons Ltd., and Air Commodore Stanford Cade from the latter's book, "Malignant Disease and Its Treatment by Radium." I am most grateful for this permission.

In my treatment of intra-cavitary, interstitial and superficial radium therapy, I have made considerable use of the text and illustrations of the original work published by the workers at the Holt Radium Institute, Manchester, under the direction of Mr. Ralston Paterson. It gives me pleasure to acknowledge the permission to do this so readily given by Mr. Paterson.

The original photographs I have used are the work of Mr. N. H. Pierce, my technical assistant at Westminster Hospital. I wish to thank him for producing these and also for the most valuable assistance he has given me during the ten years of our work together.

The original manuscript was read by Professor Sidney Russ, who made many valuable suggestions which I have acted upon. I am pleased to acknowledge this and his kind interest in the preparation of the book.

I should like to take this opportunity of thanking my senior colleagues at Westminster Hospital, namely Sir Ernest Rock-Carling, Air Commodore Stanford Cade and Dr. F. M. Allchin on the medical side, and Professor H. T. Flint, who is honorary physicist to the hospital, for the encouragement they have always given me, and for the freedom of expression they have always allowed in the clinical, as well as physical aspects of my work.

Last, but most certainly not least, I should like to express my thanks to Messrs. Chapman and Hall Ltd., for the most careful attention they have given to the production of this book. Whatever may be lacking must be attributed entirely to my deficiencies.

C. W. WILSON.

HENDON,
October, 1944.

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CHAPTER I

RADIUM—ITS PROPERTIES AND APPLICATION TO MEDICINE

1. The Nature of Radium and its Radiations

A NUMBER of naturally occurring chemical elements, which are of high atomic weight and number, spontaneously change into other chemical elements possessing a different atomic number, and this change is accompanied by the emission of energy in the form of electromagnetic wave radiation together with corpuscular radiations. These elements are called radioactive and radium is one of them.

Chemically radium reacts with other elements as a metal resembling barium, and it is usually used in medicine in the form of the compounds radium sulphate, radium chloride and radium bromide. The pure metal is not available, but the compounds behave with regard to their radioactive properties in the same way as does the element itself. It is the amount of radium element in a quantity of salt with which one is always concerned in medicine because it is this which gives rise to the radiations.

Radium is found in very small amounts in the black mineral pitchblende, which is chiefly uranium oxide. This is found mainly in Bohemia, Saxony, East Africa and Canada. Formerly most of the radium used derived from Katanga in the Belgian Congo, but in recent years the source discovered in the region of the Great Bear Lake in Canada has proved of some consequence and Canadian radium is being used more and more.

Radium was first isolated from pitchblende by Madame Curie. The separation, which involves a large number of fractional crystallizations, is a costly and laborious process, since only a few milligrams of radium are present in a ton of even the richest mineral.

It has been shown that the radioactivity of radium and the other radioactive elements is independent of their physical state as well as their chemical combination. Because of this radioactivity was taken to be an atomic phenomenon peculiar to the atoms of these heavier elements.

For an appreciation of the principles of radioactive transformation it is necessary to discuss briefly present ideas concerning the structure of atoms. It is believed, in view of the evidence available, that every atom consists of a central, positively charged, heavy nucleus which contains practically all the mass of the atom, around which a number of comparatively light *electrons* rotate in various orbits. Electrons are negatively charged particles which exist in various states of binding in the various atoms and in certain circumstances they may be removed from their atoms, as is the case in the cathode ray tube, the thermionic valve or the photo-electric cell.

Since every atom is electrically neutral there is a sufficient number of electrons in each atom for their total negative charge to balance exactly the positive charge of the nucleus. The simplest atom is that of hydrogen, which has a single orbital electron so that its nucleus has a positive charge equal to that on the electron. The latter may be considered as a unit of electric charge. This hydrogen nucleus is known as a *proton.* Its mass is practically equal to that of the whole atom, which is unity (to a very close approximation) on the chemists' scale. The proton is therefore a heavy particle of unit atomic mass bearing unit positive charge.

Next in simplicity of structure is the atom of helium, which has two orbital electrons, so that its nucleus bears two positive units of charge. The mass of this nucleus, however, is four of the atomic units. In certain circumstances, as we shall see, the atom of helium may be obtained free of its outer electrons. It is then referred to as an *α-particle.* An α-particle is therefore a heavy particle of four units of atomic mass bearing two units of positive charge.

At one time it was considered that protons and α-particles were the main building units from which all atomic nuclei are constructed but research carried out since 1930 has shown that an α-particle is itself made up of two protons and two other particles, which have the same mass as a proton, but which are electrically neutral. These particles are known as *neutrons*, and it is now considered that every atomic nucleus is built of specific numbers of protons and neutrons.

A quantity that is used a great deal in the physics of radioactivity is the atomic number of an element. The atomic number of any element is the number of unit positive charges on the nuclei of the atoms of that element. Thus, for instance, the atomic number of hydrogen is 1, that of helium 2. It follows, naturally, that the atomic number is also equal to the number of extra-nuclear electrons in the individual atoms.

All the radioactive elements are of high atomic number and atomic weight, the values being 88 and 226 respectively in the case of radium. The nuclei of these elements therefore consist of quite large numbers of protons and neutrons, and this complexity results in considerable instability. Because of this instability the elements undergo spontaneous disintegration in which an atom changes into a different atom which is less complex than its parent. These transmutations are accompanied by the emission of energy of one form or another. A series of such disintegrations may occur until a stable nuclear structure is reached.

The energy released in the process of such transmutation is emitted as radiation, which may be of three types. It may be emitted in the form of alpha rays, beta rays and gamma rays.

Alpha rays are α-particles which are ejected from the nuclei of the disintegrating atoms with velocities of the order of one-twentieth of that of light (the velocity of light is 186,000 miles per second). Alpha rays are therefore really helium nuclei, a fact which has been confirmed by passing a spark discharge through a vacuous space into which α-rays had been allowed to pass. The spectrum obtained from the discharge was that of helium.

In their passage through air or other gas α-rays ionize the gas very intensely so that they quickly lose energy. The fastest α-particles from radium travel up to 7 cm. in air, but are stopped by a few thicknesses of cigarette paper. Because of their small penetrating power α-rays are of little therapeutic value.

A useful method of detecting α-particles is by means of the fluorescence they produce on striking various minerals such as zinc sulphide. If the α-particles are sufficiently few it is possible to observe individual impacts of α-particles on the fluorescent materials by means of a low power microscope. It is possible to count α-particles by means of such scintillations. Another useful method for the detection of these particles is by means of their photographic effect.

Beta rays are electrons which are emitted from the disintegrating nuclei with various velocities. The slowest (soft beta rays) have a velocity of about one-sixth of that of light, while the speed of the fastest (hard beta rays) is only slightly less than that of light. The beta rays are identical in character with the cathode rays which produce X-rays in the sense that they are high-speed electrons. Since their mass is only one-eighteen-hundredth of the mass of an α-particle, beta rays have a penetrating power about 100 times greater than that of α-rays, and the fastest can pass through 1 cm. of aluminium and an even greater thickness of tissue. For this reason beta rays are sometimes used in the treatment of superficial lesions, the radium source being lightly screened to permit the passage of these rays. Such use, however, is strictly limited and is not of much consequence in general radium therapy.

Like α-rays, beta rays affect a photographic plate and ionize gases. The intensity of ionization, however, is much less for beta rays than for α-rays. Since α-rays and beta rays are electrically charged, they can both be deflected by a magnetic field, the α-rays being bent in a direction opposite to that of the beta rays.

Gamma rays are different from α-rays and beta rays in that they are undeflected in a magnetic field. They are a true electromagnetic radiation similar in nature to visible light and X-rays, and they travel with the same velocity. The gamma rays which derive from radium and its products consist of radiations having a wide range of penetrating power. The most penetrating or hardest of the gamma rays are able to pass through 15 cm. of lead, having a wave-length that is much shorter than the wave-lengths of the hardest X-radiation.

It is with the gamma rays that modern radium therapy is primarily concerned, and it is upon these that we shall fix our attention throughout this book. In their passage through matter the gamma rays interact with the atoms, the interaction giving rise to high-speed electrons, which are called secondary corpuscular radiation. It is this secondary corpuscular radiation which is responsible for the effects produced by the radiation such as ionization in gases and the biological effect in tissues. Gamma rays may therefore be used as an agent to convey energy to deep-seated tissues, where this energy is transformed into a biologically active radiation.

2. Radioactive Series

Radium is a member of a series of radioactive elements. It derives from the successive transformation of parent substances, and, as a result of its own decay, is itself a parent to a number of radioactive substances. There are three main radioactive series: the Uranium, Actinium and Thorium series. Radium belongs to the first of these series, which is the only one used in practical radiotherapy. The members of this series are listed in order of their sequence in Table 1, together with the radiations emitted at each transformation, the rates of decay and the amounts of each in equilibrium with 1 gram of radium.

It will be seen from Table 1 that radium first transforms into radon, which is a gas, by the emission of an α-particle. The radon atoms emit α-particles and thereby are transformed into radium A, which is a solid. Radium A in turn emits α-particles to produce radium B, another solid. Radium B transforms into the solid radium C with the emission of beta rays and weak gamma radiation. Radium C changes into another solid, radium D, with the emission of α-particles, beta rays and a strong gamma radiation. These transformations take place within a relatively short space of time. Those which follow (see Table 1) take much longer and give rise to little gamma radiation, so they are of little consequence to gamma ray therapy. The various solids which derive from the decay of the gas radon are usually referred to as the active deposit of radon.

We see that gamma rays are not emitted in the disintegration of

TABLE 1.—*Elements of the Uranium Series* (Eddy and Oddie[1])

Element	Atomic weight	Atomic number	Particle emitted	Gamma rays	Rate of decay	Amount in equilibrium with one gramme of radium
Uranium I	238	92	α	—	0·000000015% per yr.	2,830 kgm.
Uranium X	234	90	β	Weak	3·3% per day	0·04 mgm.
Uranium X_2	234	91	β	Weak	1·0% per sec.	0·0013 microgm.
Uranium II	234	92	α	—	0·0003% per yr.	1·18 kgm.
Ionium	230	90	α	—	0·001% per yr.	41 gm.
Radium	226	88	α	—	0·044% per yr.	1 gm.
Radon	222	86	α	—	0·75% per day.	0·25 microgm.
Radium A	218	84	α	—	0·38% per sec.	0·0034 microgm.
Radium B	214	82	β	Weak	2·6% per min.	0·030 microgm.
Radium C	214	83	β	Strong	3·5% per min.	0·022 microgm.
Radium C^1	214	84	α	—	Very fast	Very small
Radium D	210	82	β	Weak	4·3% per yr.	9·8 mgm.
Radium E	210	83	β	Weak	0·60% per hr.	8·1 microgm.
Polonium	210	84	α	—	0·51% per day	0·22 mgm.
Lead	206	82		—	Stable	

radium itself; they are only emitted by the solids radium B and radium C, which are formed as a result of the decay of radium. These solids really derive from the gas radon, which is produced by the disintegration of radium. Thus, if a radium source is to reach its condition of maximum gamma ray activity, it must be hermetically sealed to prevent the loss of radon. Further, the gas radon, so far as gamma radiation is concerned, may be looked upon as the " radiation essence " of radium. This fact is made much use of in radium therapy for, as we shall see, it enables one to use a source of radon in cases where it is undesirable to use a source containing radium element.

When radium is sealed in a container such as a needle so that none of its subsequent products can become dispersed, a state of affairs will be reached after a suitable interval of time when the rate at which a disintegration product is formed is equal to the rate at which it decays. This state of affairs, when there will be fixed amounts of each of the disintegration products present, is termed *radioactive equilibrium.* Thus when equilibrium is established in a radium needle, the radium C, which is the important source of gamma rays, has reached its maximum value. About one two-thousandth of the radium atoms in the needle per year pass through the series of transformation products. Thus the available energy in the needle is dissipated at the rate of one two-thousandth per year, and the intensity of the radiation also decreases at this rate.

When freshly prepared radium is sealed in a needle some time is required for the disintegration products to accumulate and reach radioactive equilibrium. Hence the gamma ray emission of a new tube may be quite small, but gradually increases with time, reaching within one-thousandth of its equilibrium strength in about thirty-five days after sealing.

3. Growth and Decay of Radioactive Elements

In general, any radioactive substance decays at a fixed rate, which is characteristic of the substance. The decay follows an exponential law, that is, if within a certain time half the number of atoms of a particular substance have disintegrated, then in a following equal time half of the remainder will disintegrate, and so on. This law is indicated more clearly in the curve A of Fig. 1, which illustrates the decay of radon.

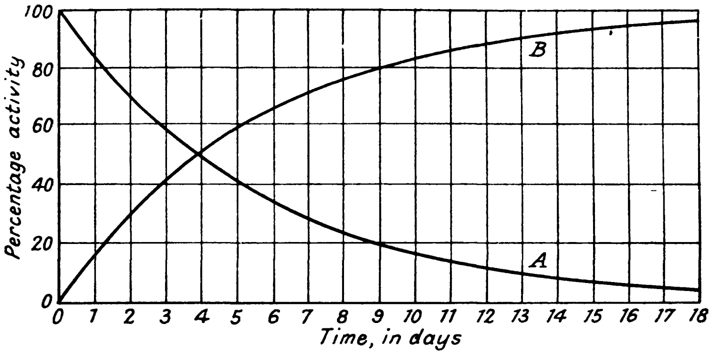

FIG. 1.—Curves showing the growth (B) and decay (A) of radon.

The exponential law of disintegration may be expressed mathematically by the equation :—

$$N = N_0 e^{-\lambda t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where N_0 is the original number of atoms, N is the number remaining after a time t, e is the base of Naperian logarithms (= 2·718) and λ is a constant for the particular substance being considered, which is known as the transformation constant. This constant has different values for different substances.

The growth of a new substance as the result of the decay of its parent is expressed by the equation :—

$$N = N_0 (1 - e^{-\lambda t}) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where N_0 is the maximum number of atoms that is finally attained and N is the number after a time t. The curve of growth for radon is given as curve B of Fig. 1, from which it may be seen that the radon produced by its parent radium is approaching its maximum amount after a period of about eighteen days or more. The transformation or decay constant λ of radon is 0·181 per day.

The time required for one-half of the atoms of a radioactive substance to have undergone disintegration is known as the *half life period* of the substance. It may be shown that the half life period, which we shall call T, is related to the transformation constant of the substance by the equation $T = \frac{0 \cdot 693}{\lambda}$. For radon the half life period is 3·82 days.

The individual atoms of a radioactive element have periods of existence of all possible values from zero to infinity. In practice, however, we may speak of the *average life* of a large number of atoms. It is possible to show that the average life of the atoms of a substance having a decay constant λ is equal to $\frac{1}{\lambda}$, *e.g.*, the average life of the atoms of radon $= \frac{1}{0{\cdot}181}$ days $= 5{\cdot}52$ days.

4. Radon

Radon, the substance produced by the transformation of radium, is a heavy, colourless, inert gas belonging to the family of helium, argon, etc. It has an atomic weight of 222 and an atomic number of 86. At temperatures below $-\ 71^\circ$ C. it solidifies, but at temperatures above $-\ 61{\cdot}8^\circ$ C. it is gaseous. It has a vapour pressure similar to other gases.

Radon is exceedingly important in therapy because, as we have seen, the solid active deposits of radium B and radium C, which are the source of gamma rays, arise from radon. Thus a source of radon, when its full amount of active deposit is formed, is as good a source of gamma rays as is radium in a sealed container. The essential difference is that the activity of radon decays relatively quickly (Fig. 1) compared with radium, the decay of which is negligibly small.

The most used unit of measurement of radon is the millicurie (mc.), which is the amount of radon in equilibrium with 1 mgm. of radium element. Since two similar tubes which contain at any given time 1 mc. of radon and 1 mgm. of radium respectively will contain equal amounts of the disintegration products, the tubes will emit equivalent intensities of gamma rays. It is important to realise, however, that owing to the very different decay rates of radon and radium, equivalent gamma ray intensities will not be emitted at other times.

5. Relation between Radium and Radon Dosage

In order to estimate dosage with radon relative to what it would be if radium was used, allowance has to be made for the relatively rapid decay of the radon, *i.e.*, a method has to be used which relates the radiation emitted from a quantity of radon to that emitted from radium.

Thus, suppose we have 1 mgm. of radium, then in one hour the radiation emitted from the radium is proportional to the product 1 mgm. × 1 hour, which is usually called 1 mgm.-hour. Similarly, the radiation from 5 mgm. of radium in ten hours would be proportional to 50 mgm.-hours.

Now the radiation equivalent to 1 mgm.-hour is proportional to the number of atoms changing per hour × 1 hour, *i.e.*, proportional to $\lambda N_0 \frac{1}{24}$, where N_0 is the number of atoms in 1 mc. of radon (in equilibrium with 1 mgm. of radium) and λ is the decay constant of radon expressed in days.

Similarly, when 1 mc. of radon is destroyed (from time = 0 to time = ∞) the total radiation emitted is proportional to the number of atoms changed, that is, it is proportional to N_0.

$$\text{Thus 1 millicurie destroyed} = \frac{N_0}{\lambda N_0 \frac{1}{24}} \text{ mgm.-hours.}$$

$$= \frac{24}{\lambda} \text{ mgm.-hours.}$$

But $\frac{1}{\lambda}$ is the average life of the atoms of radon and = 5·52 days, so that 1 millicurie destroyed (mc. d.) = 24 × 5·52 = 132·4 mgm.-hours.

In some cases radon is inserted into tissues in the place of radium and left *in situ.* In such cases it is obvious that the total radiation is equal to that given out when all the millicuries inserted are destroyed. Thus, for example, if 15 millicuries are inserted in this way the total radiation is equivalent to 15 × 132·4 = 1,936 mgm.-hours. Whether the same equivalence holds biologically is doubtful, for with the radon the intensity of radiation would vary throughout the treatment from its original maximum value down to zero.

If the radon is not left in permanently, but is removed at the end of a certain time, the number of millicuries destroyed is obtained by subtracting the millicuries remaining at the time of removal from those originally used. The final value can be deduced by means of the curve A of Fig. 1, or, better still, from the table given in Appendix I. This table is derived from the curve. For example, supposing 10 mc. are used for twenty-four hours. The final strength at the end of the period is 8·34 mc., so that 1·66 mc. were destroyed and the equivalent milligram-hours = 1·66 × 132·4 = 220 mgm.-hours.

As another alternative, it is the custom with some workers to refer to the average strength of the source during the time of treatment. In the last example this would be 9·17 mc.

Yet another method which is sometimes used is to begin treatment with a rather larger quantity of radon than the radium equivalent, so that the same dose is obtained for the same time of exposure. This would be done when the time factor is considered all-important.

6. Extraction of Radon

Radon is not liberated very easily from the solid salts, and so it is usually obtained from a solution of either radium chloride or radium bromide dissolved in dilute hydrochloric acid. One gram of radium in solution produces per diem about 0·0001 c.c. of radon mixed with about 50 c.c. of gaseous impurities, largely composed of hydrogen and oxygen with traces of organic vapours, carbon dioxide, hydrochloric acid, water vapour and helium.

Because radon is soluble in water it is necessary to keep the volume of the radium solution as small as possible, but to obtain a high yield a reasonably large surface and volume above the surface into which the gas may escape should be provided. The relative amounts of radon in the solution and above it depend upon the volume of the containing vessel, the volume of the solution and the temperature. As an example, at a room temperature of 17·5° C. with 200 c.c. of solution in a flask of 500 c.c. volume, about 16 per cent. of the radon will be dissolved in the liquid.[1] The glass flask containing the solution is usually surrounded by a beaker to prevent loss in case of breakage and a suitable thickness of lead for protection from the gamma rays.

For therapeutic use radon is usually not chemically pure, but sufficient of the impurities is removed to enable the residual gases to be introduced into the small volume of the container at less than atmospheric pressure. In practice it is found that carbon dioxide is removed only with great difficulty, so that an efficient apparatus should have as few taps and ground glass joints as possible in contact with the gases, so that production of carbon dioxide from tap grease is a minimum.

Many methods of purifying radon have been described by various authors. One of the most recent of these methods, described by Oddie,[2] has much to recommend it from the point of view of routine hospital practice. The apparatus described is designed to deal with 2 grams of radium in solution, from which, during a weekend, some 1,000 mc. of radon are produced. Oddie[2] gives a very comprehensive list of the literature dealing with the extraction of radon.

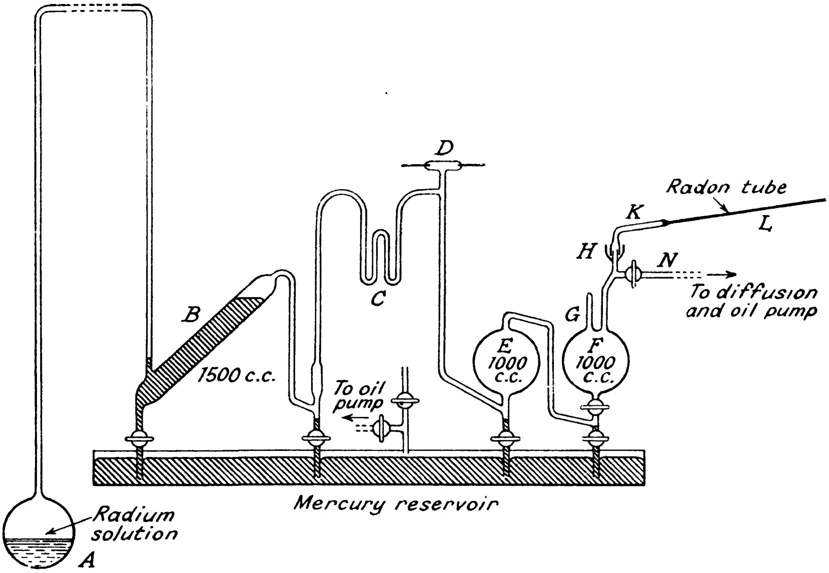

FIG. 2.—Schematic diagram of apparatus for the purification of radon (Oddie[2]).

The apparatus is first evacuated to a very low pressure of the order of 10^{-6} mm. of mercury. The gas mixture from the radium flask is passed through C which is cooled by immersion in a Dewar flask containing solid CO_2 and acetone to freeze out water and other vapours, into both bulbs E and F. Three strokes on the Toepler pump E serve to transfer all the gases to F. The mercury is allowed to run nearly to the top of F, just below the portion G, which is filled with liquid air. Ten minutes are allowed for the freezing of the radon and CO_2, when the volatile gases are pumped off in a few seconds through the side tube N. After boiling off the liquid air, the gas is pushed in to the tube K, the walls of which are coated with fused KOH, which is gently warmed to accelerate the removal of CO_2. Finally the purified radon is passed into a length of capillary tubing L. This capillary might be glass or gold.

The main processes involved in the various methods of purifying radon may be summarised as follows[2] :—

(I) Removal of organic vapours—by oxidation to form water and carbon dioxide.

(II) Removal of carbon dioxide—by absorption with either potassium hydroxide or metallic calcium.

(III) Removal of water vapour—chemically, by absorption with phosphorus pentoxide or metallic calcium and physically by freezing with solid carbon dioxide. In some cases the water vapour is not removed, but allowed to condense on the walls of the apparatus.

(IV) Removal of hydrogen and oxygen—by absorption with metallic calcium, or by recombination by sparking or by passing over hot copper and copper oxide or a hot platinum wire.

The apparatus described by Oddie,[2] which is shown diagrammatically in Fig. 2, yields radon that is much more than sufficiently pure for therapeutic uses. The strengths of radon seed usually used are up to 3 millicuries per centimetre length of tube, and the purification obtained permits up to 7 millicuries per centimetre length.

It is important that the time taken for the extraction shall be as short as possible, since the exposure to the operator is then reduced to a minimum, especially because the amounts of the active deposits of radium (B + C) present are then kept to a minimum. When radon is first prepared within a container the gamma ray activity is zero. This activity gradually increases as radium B and radium C are progressively formed until after about four hours maximum activity is reached when the active deposits are in equilibrium with the parent radon. From this time onwards the radon decays exponentially, falling to half its maximum value in 3·82 days.

7. Radium and Radon Containers used in Medicine

For clinical purposes radium is usually mounted in the form of needles, tubes and plates or plaques, the insoluble radium sulphate being most commonly used. The strength of the source is referred to as of so many milligrams of radium element. The relative proportion of radium in the salts most frequently used are given in Table 2. Often, to ensure complete and uniform filling of the container, the salt is mixed with inert materials of low atomic weight.

Mesothorium, one of the substances of the thorium series, is often associated with radium and is an undesirable impurity. It

TABLE 2

Salt	Percentage of radium
Radium sulphate $RaSO_4$	70·2
Radium chloride, anhydrous $RaCl_2$ . .	76·1
Radium chloride $RaCl_2 . 2H_2O$ . . .	67·9
Radium bromide, anhydrous $RaBr_2$ . .	58·6
Radium bromide $RaBr_2 . 2H_2O$ . . .	53·6

is an isotope of radium and so cannot be separated from it by ordinary chemical methods. It also emits gamma rays, which may be confused with the radiation from the radium, but it decays more rapidly at the rate of about 10 per cent. per annum.

Plaques often have only a light filtration (0·2 mm. of monel metal), since they are used mainly for superficial therapy. Some beta rays are then included with the gamma radiation, and this use does not strictly constitute gamma ray therapy. The beta rays become weaker through succeeding layers of tissue due to their absorption and spread from the source.

The walls of needles and tubes are most often made of iridio-platinum, but occasionally steel, monel metal or other suitable metals are used.

Sectional diagrams illustrating the construction of typical radium needles and tubes are shown in Fig. 3. The needles consist of an

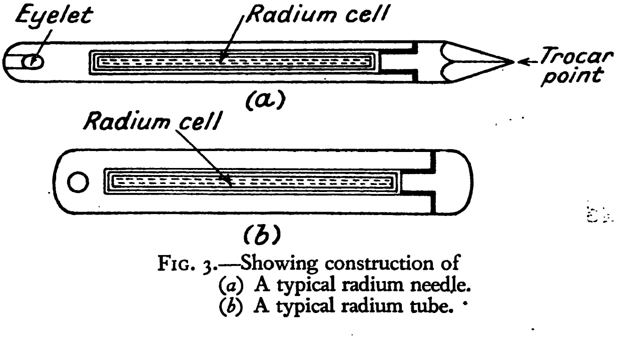

FIG. 3.—Showing construction of
(*a*) A typical radium needle.
(*b*) A typical radium tube.

iridio-platinum outer body with an eyelet at one end and a trocar point at the other and the radium is contained in one or more iridio-platinum cells within this body. The radium is distributed uniformly along the active length of the needle. Tubes closely resemble needles except that they do not have a sharp point and do not usually need to have such a small diameter as is preferable for needles. For this reason greater thicknesses of a cheaper metal (*e.g.*, silver) than platinum may be used to furnish the filtration of tubes.

Radon is mounted by two main methods. In most institutions in this country it is the practice to collect the radon in fine glass capillary tubing which is then parted into small lengths of 3 to 4 mm. by means of a micro-flame. These small lengths of capillary tube are put into small platinum or gold cases, as illustrated in Fig. 4, the open end being closed by burring over the soft metal. The finished article is described as a radon seed. The cases may have screenage or wall thickness of 0·3 or 0·5 mm. as required. If necessary a light string can be attached at one end of the seeds, so that they may be pulled out of the tissue after use. It is possible, if the occasion arises, to put a string at each end of a seed for tying in position after the seed has been introduced into the tissues.

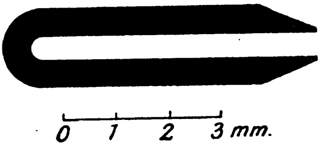

Fig. 4.—Section of radon seed case.

The other method of mounting radon is by means of gold tubing. This was first introduced by Failla (General Reference ^{5}) in America and for various reasons [1] it has been adopted in Australia. A few institutions use it in this country. In this method the purified radon is put into fine capillary tubing of pure gold and is subdivided by merely snipping with a pair of blunt-edged pliers, pure gold having the property of being autogenously welded under pressure. Full details may be found in the publication [1] already referred to.

For interstitial work radium needles seldom exceed much more than about 1 mgm. of radium per centimetre of active length and radon seeds seldom contain more than 2 millicuries of radon, but for some other purposes the concentrations may be much greater.

Details of some of the types of radium needles in use at Westminster Hospital are given in Table 3.

TABLE 3.—*Specification of Some Westminster Hospital Radium Needles*

Amount of radium	Overall length	Active length	Filtration in mm. platinum	External diameter
mgm.	mm.	mm.	mm.	mm.
0·6	16·0	8·0	0·5	1·6
1·0	24·5	16·3	0·8	2·0
1·33	27·0	19·0	0·6	1·8
2·0	33·0	25·0	0·65	1·9
2·0	42·5	35·0	0·80	2·0
3·0	51·5	44·0	0·80	2·0

8. Relative Merits of Radium and Radon

In their therapeutic use, radium and radon each have advantages and disadvantages.[1] The most important of these would seem to be :—

Advantages of radium :—

(I) A constant radiation intensity is emitted which may be useful biologically and dosage calculations are simpler.

(II) Once prepared, radium containers can be used for a number of years without much further technical assistance.

Disadvantages of radium :—

(I) On account of its value, special arrangements must be made for its safe storage in and out of use and patients undergoing treatment must be kept in hospital to prevent possible loss.

(II) Radical changes in radium distribution for a new technique involves considerable expense and the withdrawal from use for some time.

Advantages of radon :—

(I) Only the comparatively valueless radon is used in the treatment itself.

(II) Patients can return home with radon sources in place.

(III) Radon may be introduced into containers of almost any required shape and dimensions.

(IV) If necessary, radon seeds may be left in the patient permanently.

Disadvantages of radon :—

(I) The radiation from a radon source decreases comparatively quickly and continuously so that the dosage-rate is not constant. Dosage calculation is made more difficult.

(II) A radon laboratory, with a specially trained staff, is required.

9. Screenage or Filtration of Radium Sources

Iridio-platinum is usually preferred for the walls of radium tubes and needles because the container is then not destroyed if by accident it is incinerated with dressings and other waste and because it is possible to obtain the necessary filtration with quite thin walls. Steel and monel metal have greater mechanical strength than iridio-platinum. A minimum wall thickness of 0·4 mm. iridio-platinum, or 0·3 mm. of steel or monel is necessary for sufficient rigidity; 0·6 mm. is recommended for needles longer than 40 mm. The minimum thickness now usually used is 0·5 mm.*

It has been found clinically that increase of the screenage to 0·8 mm. platinum has led to marked improvement in the results of interstitial therapy. This can be due only very little to hardening of the gamma rays and is most probably due to the increase in distance that is effected between the radium and the tissues in contact with the needles. There are obvious limits to the increase in screenage that may be used because of the difficulty of introducing needles that are very thick into the tissues. The question of screenage in so far as secondary radiations from the metal are concerned is considered later (Chapter V).

10. The Gamma Rays from Radium (B + C)

The gamma radiation emitted by the radioactive atoms of radium consists of a number of definite wave-lengths, forming a line spectrum. The main wave-lengths present in the line spectrum of the gamma radiation from radium B and radium C are given in Table 4, which also gives the relative energies or intensities of these lines. The wave-lengths are expressed in units of 10^{-11} cm., which are known as X units (X.U.).

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* Dr. G. J. Neary (*British Journal Rad.*, Vol. 15, 1942, p. 104) has shown that "for needles or flat applicators of 0·5 mm. platinum screenage, the ionization of the primary beta radiation in the adjacent tissue is never more than a few per cent., and is in any case much less than the ionization of the secondary beta radiation from the filter."

In addition, column 3 gives the quantum energy of the various wave-lengths in electron-kilovolts, that is, the potential in kilovolts it would be necessary to apply to an electron in order that it might generate X-radiation of that particular wave-length. It is seen that the softest lines (from RaB) correspond to potentials up to about 350 kv., whereas up to 2,000,000 volts is needed to generate wave-lengths as short as those of the hardest lines (from RaC).

TABLE 4.—*Wave-lengths Present in the Ra (B + C) Spectrum. Their Relative Energies and Equivalent Potentials* (Mayneord [3])

Wave-length in X.U. (1X.U. = 10^{-3} A.U. = 10^{-11} cm.)		Energy of line as percentage of total energy	Quantum energy in electron kilovolts
50·8	RaB	1·55	243
41·6		4·26	297
34·9		8·82	354
20·2	RaC	22·35	612
16·0		2·79	773
13·1		3·47	941
10·92		12·91	1,130
9·89		4·29	1,248
8·89		4·91	1,390
6·94		25·5	1,778
5·57		9·15	2,219

11. The Measurement of Radium and Radon

A radium or radon source is measured by comparing the gamma radiation it emits with the radiation from a standard source of radium. This comparison of emitted radiations is done by comparing the ionizations in air which the radiations produce. When the gamma rays pass through air they cause the ejection of secondary corpuscular rays as we have seen already. These secondary rays, or, more strictly, secondary particles, which are energetic electrons, further interact with the gas molecules expelling electrons in some cases and attaching themselves to molecules in other cases. By these processes negatively and positively charged molecules are produced which are known as gaseous ions, that is, the gamma radiation is said to ionize the air. The electric charge thus liberated is proportional to the energy abstracted from the radiation, and this in turn is proportional to the intensity of the radiation.

The International Standard for radium quantity was established in 1912 by La Commission Internationale de l'Etalon du Radium. It is a glass tube containing 16·74 mgm. of radium prepared by Madame Curie and kept in the Bureau Internationale des Poids et Mesures at Sèvres, near Paris. A Reserve International Standard is kept in Vienna.

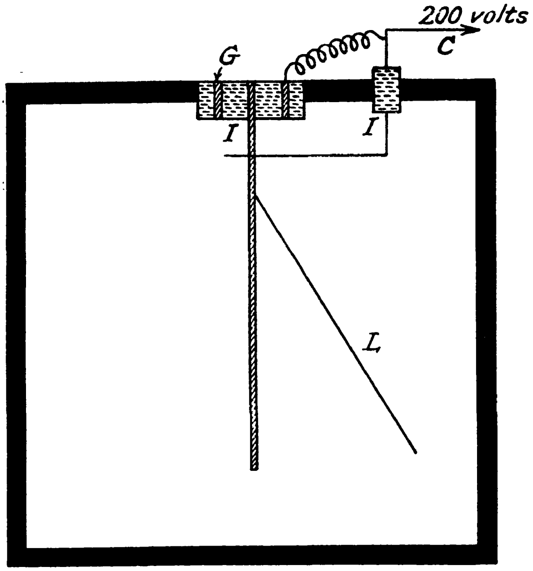

FIG. 5.—Simple gold leaf electroscope.
C = Charging wire at about 200 volts. G = Guard ring at potential of C.
L = Gold leaf. I = Amber insulation.

There are a number of Secondary Standards which have been measured by comparison with the International Standard. In England these are in the possession of the National Physical Laboratory. This laboratory will measure against their standards any source whose content is required to be known accurately. An account of their procedure has been given by Perry.[4] Since the radium is enclosed in a container of dense material, the measurement actually is a comparison of the radiation that penetrates the walls and not of the radium it contains, so that the quantity of radium is referred to as the radium equivalent. The certificate of test which is issued with a statement of the measurement usually indicates, in addition, the actual radium content after the necessary corrections for screenage have been applied.

It is also possible to have a source examined for mesothorium impurity. This is done by means of measurements made at intervals over a period of a few months. If the source is free of mesothorium the radiation measured will be constant.

In making a measurement, the ionization produced by the gamma rays of the source to be determined is compared with that of the standard when it replaces the former. For this purpose, a simple gold leaf electroscope, as illustrated in Fig. 5, may be used or an ionization chamber fitted to a suitable electrometer. Whatever method is used, corrections should be made for (*a*) the differences in the screenage of the standard source and of the source being measured, and (*b*) differences in the linear dimensions of the sources being compared.

The instrument most commonly used for the measurement of radium is some type of gold leaf electroscope. In this the gold leaf system is charged to a potential of a few hundred volts so that the leaf stands out, repelled away from its supporting rod. When the air in the electroscope is ionized by the action of the gamma rays from a radium source, charge is lost by the leaf system and the rate of loss of charge may be determined by the rate of collapse of the gold leaf. The rate of loss of charge of the electroscope is proportional to the ionization produced in the electroscope, and this is a measure of the gamma ray intensity at the electroscope provided the walls of the latter are of a sufficient thickness of lead to exclude all but gamma rays.

In an actual measurement the rate of loss of charge is determined with the standard source at a fixed convenient distance from the electroscope by timing the travel of the gold leaf across a definite portion of the scale when it is viewed through a tele-microscope. The mean of several observations is taken. The standard is replaced by the unknown source and similar observations made across the same portion of the scale. Finally, the rate of loss of charge is determined with no radium present. This gives the natural loss of charge (natural leak) of the instrument which must be subtracted from each of the previous values. The ratio of the two corrected rates of loss of charge is the ratio of the activities of the two sources, and since one is known the other is determined.

For the routine measurement of large numbers of radon seeds, the method just described suffers in that it is very time-consuming, and, in fact, cannot be used to measure all the seeds that may be sent out from a radon laboratory. For this purpose a direct reading electroscope[5] is used at Westminster Hospital. The circuit of this instrument is given in Fig. 6 and the complete instrument is illustrated in Fig. 7.* In this instrument the ionization current, produced in a large ionization chamber, is led down a high resistance of the order of 10^{10} ohms and the potential across the ends of the resistance is measured on a Lindemann electrometer as a steady deflection. A simple control circuit[6] enables the sensitivity of the instrument to be changed very easily. Thus, with the standard source in position, it is easy to set the resultant deflection to, say, 100 divisions deflection per milligram, and when the standard is replaced by, say, a radon seed, its activity is read off at once. For the purpose of ensuring that a group of radon seeds do not depart by too great a margin from their desired value, this method is extremely valuable. If it is so desired, the high resistance may be removed very simply and the instrument may be used in electroscope fashion, except that growth of charge is recorded instead of loss of charge.

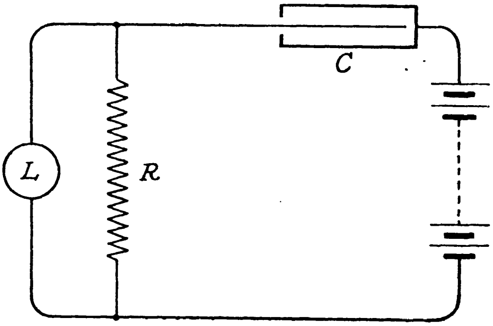

FIG. 6.—Circuit of direct reading electroscope (*L. G. Grimmett*).
C = Ionization chamber (volume 5–6 litres). R = High resistance (10^{10}–10^{11} ohms)
L = Lindemann electrometer.

Another useful direct reading meter for the same purpose has been described by Farmer.[7] This is based on a valve (Marconi

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* Facing page 22.

E.T.1) with an extremely small grid current and incorporates liquid resistances of two values so that two different ranges may be covered, viz., 0–25 and 0–100 millicuries. The apparatus is operated from two batteries, one of about 100 volts supplying the valve anode and the ionization chamber, the other a 2-volt accumulator feeding the valve filament. Both give only very small currents, so that the instrument is readily portable.

Meyer[8] has described a photographic method of measuring radium quantity of particular value for small radium quantities. Long exposure times are necessary, but no elaborate apparatus is required.

In practice, in order to minimize exposure of personnel to radiation, radon seeds may be measured some time before they have reached their maximum gamma ray activity. From a knowledge of the growth curve it is possible to calculate what the maximum activity will be, providing the time between the moment of introducing the radon into the container and the time of measurement is known. When radon seeds are sent out for medical use from the issuing laboratory, the latter states the content in millicuries at the time they will be used. If this time is some interval after the maximum activity is reached, as is usually the case, the activity at the time of use is calculated from the decay curve of radon.

12. Detection of Leaky Radium Containers

Radium needles and other sources which are in constant use should be examined carefully at least once a year in order to ensure that no serious physical damage has resulted, *e.g.*, needles may be seriously bent and thin-walled plaques may get scratched or dented. The latter especially should be very carefully handled at all times to guard against such damage. The sources should, in addition, be examined for any possible leakage of radon, particularly if they appear damaged.

A radium needle, tube or plaque which is suspected of leaking may be tested by measuring its gamma ray activity. Any appreciable decrease in its activity from the nominal value should be regarded as an indication of leakage since it means that radon is able to escape from the container and true equilibrium is not maintained. A more sensitive method is to collect active deposit from the escaping radon upon some wrapping (*e.g.*, cotton-wool) placed around the suspected container for some hours. This wrapping is tested for activity by means of an electroscope sensitive to α-radiation, which will be emitted from the wrapping if it is contaminated. The presence of radio-active material indicates a leaky container.

Another very sensitive method has been described by Zimmer and Wolf.[9] In this the source to be tested for leakage is sealed in an air-tight glass vessel with a pellet of activated charcoal, which adsorbs the escaping radon. The charcoal is removed and tested for its activity by means of its effect upon a photographic film or plate.*

Leaking containers should be withdrawn from service, hermetically sealed in a stout-walled glass tube and the repair entrusted to specialists in such work. Leaks may also be detected photographically as is described in the next section.

It has been found that the longer and thinner the needles the greater the risk of damage, and, in addition, that needles which have been repaired are more likely to be damaged again, since the repairs rarely restore the original mechanical strength.

13. The Distribution of Radium Salt in Containers

The uniform distribution or otherwise of the radium salt in radium containers, may be studied by radiograms made by means of the gamma rays from the salt within the container. Russ and Clephan,[10] for example, published radiograms which showed the faulty distribution of the salt within radium needles, so that instead of a continuous line being recorded on the photographic film, a number of breaks were observed. These radiograms were made by laying the needles on a wrapped X-ray film for two minutes. The blackening thus obtained on the developed film indicates the type of distribution.

If the radium exposure is carried out on a naked film in the dark and then followed by a suitable exposure to light with the needle still in position, a radiogram is obtained which shows the needle as well as the distribution within it. Fig. 8 shows such radiograms of satisfactorily and badly packed needles and tubes, which are reproduced from a paper by Griffith.[11] This author has also used

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* The author is indebted to Mr. H. D. Griffith for bringing this method to his notice. It is used at the Radon Centre in the University of Aberdeen, and is found to be very satisfactory.

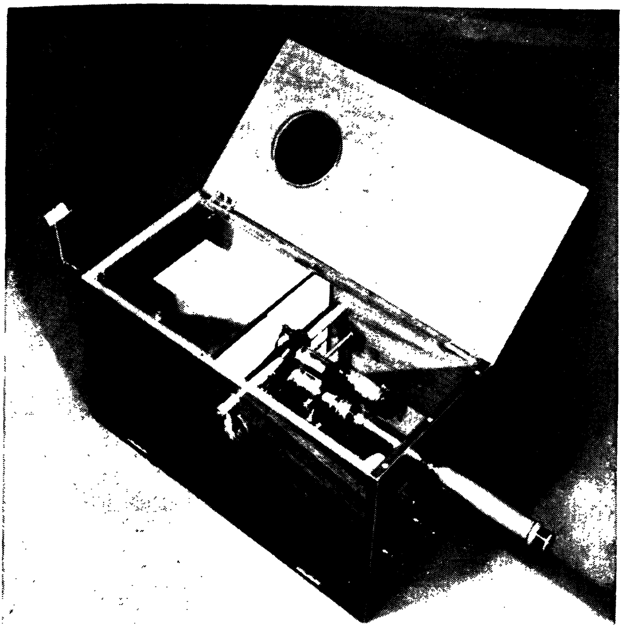

Fig. 7.—Direct reading instrument for the measurement of radium and radon-sources.
(*Grimmett.*)

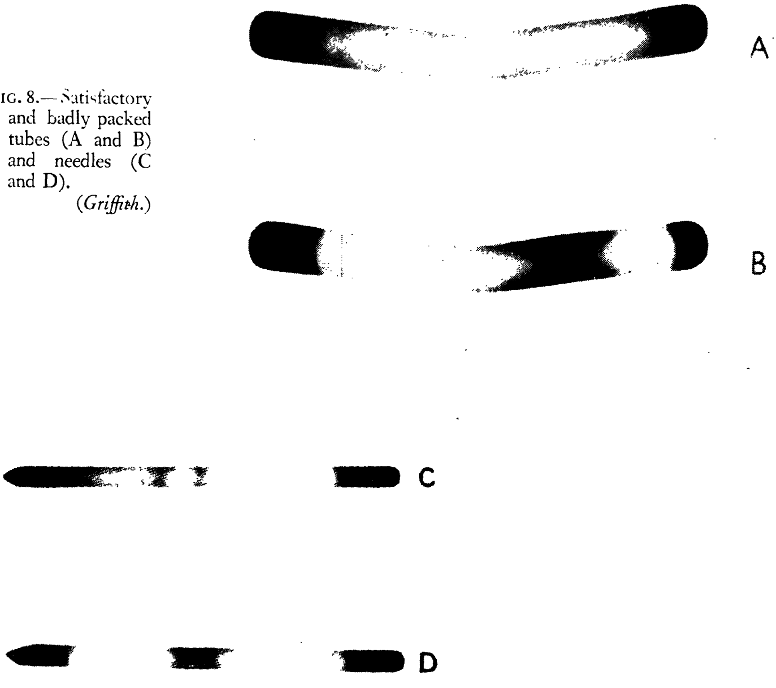

Fig. 8.—Satisfactory and badly packed tubes (A and B) and needles (C and D).
(*Griffith.*)

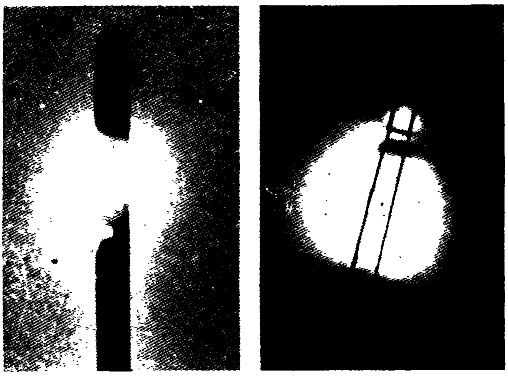

FIG. 9.—Appearance suggesting leaks in needles. (*Griffith.*)

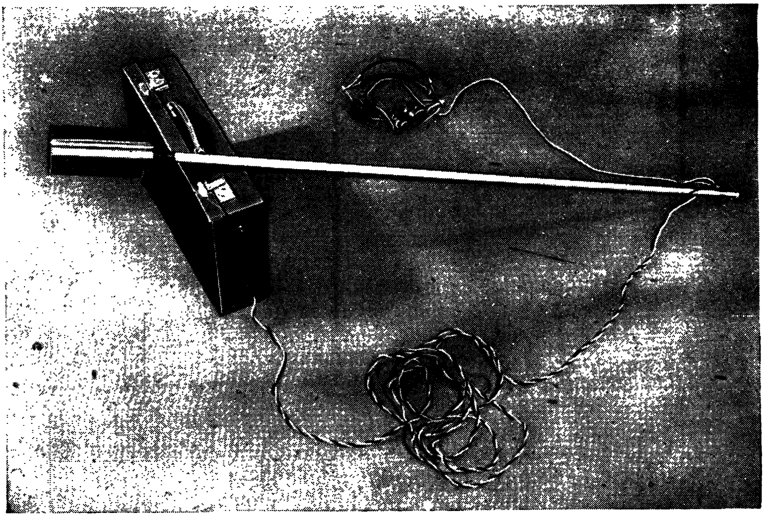

FIG. 11.—Portable apparatus (" clucking hen ") for detecting lost radium.

[*Facing p.* 23.

the method for the detection of leaks in needles, and Fig. 9 illustrates the type of radiogram that suggests a leak in a needle. A faulty distribution of radium within a needle will obviously affect the physical conditions of treatment if such a needle is used. Griffith[11] has made calculations which illustrate effects such as these.

14. Safety of Radium

It often happens in hospital work that radium sources are not given the care for their safety that their value merits. Opportunities for loss are many in a busy hospital, and losses may be avoided only by the exercise of scrupulous vigilance, particularly as the safety of the radium has to be assured from the time it leaves the safe to go to the patient until it returns to the safe; during this time it may pass through a number of hands.

It is necessary, therefore, to arrange a system for this handing on of the radium such that some specific person is always responsible for its custody, a written record of reception and return being made at every transfer from one individual to another. The actual routine decided upon will probably vary from one institution to another, but in planning it one should endeavour to cover all possibilities.

An account of the system worked out and found satisfactory at Middlesex Hospital, which will prove a useful guide for anyone considering the necessities of such a system, is to be found in the book by Russ, Clark and Watters (General Ref. 3).

15. Search for Lost Radium Containers

In spite of the greatest care, radium containers may be accidentally lost by removal from the ward or theatre among the

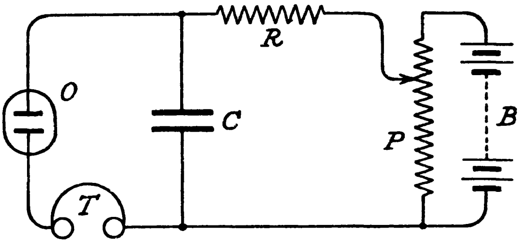

FIG. 10.—Circuit of "clucking hen" detector of lost radium. (*Chalmers.*)
O = "Osglim" lamp. C = Capacity; 0·05–0·1μF. R = Resistance; 0·25–0·5MΩ. T = Telephones. P = Potentiometer. B = Dry battery; 180 volts.

refuse, or, as has happened on more than one occasion, they may be washed down a sink to become lodged in the trap beneath.

Lost containers may be searched for and detected with either some form of electroscope or Geiger counter. A most convenient instrument for purposes of radium search is that described by Chalmers.[12] The circuit of this is shown in Fig. 10. The instrument depends for its working upon the fact that a neon " Osglim " lamp will arc over, due to the ionizing effect of gamma radiation, if the potential difference between the electrodes of the lamp has a certain value. The necessary potential difference is applied periodically across the fixed condenser, the period depending upon the capacity of the condenser and the value of the high resistance in the circuit. An interrupted current is therefore produced which gives a " cluck-cluck " sound in the telephones. The potential applied across the potentiometer is adjusted so that only a few clucks are heard per minute, due to natural radiation. When the lamp is brought within the region of a radium needle (up to 10 ft. distance or more), clucks are heard very much more frequently, and when it locates the site of the needle the clucking is practically continuous. It appears that some " Osglim " lamps are more suitable than others, and in constructing an instrument it is preferable to have a number from which to choose.

A convenient form of the instrument is shown in Fig. 11. The lamp, which is screened from visible light by enclosing it in a tin, is mounted on the end of a long wand, and is attached by a length of flex to the main body of the instrument, which is in an attaché case. This enables one to search conveniently within incinerators and other such places where radium lost in dressings most frequently come to rest.

The aim should be to prevent any loss of radium, and a very sound procedure to this end would be to have all dressings from radium wards, etc., wheeled by such an instrument to ensure that no radium is being inadvertently removed. In any case, the shorter the interval between the time at which a needle is lost and the time at which the loss is reported the greater are the chances of recovery.

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CHAPTER II

THE INTERACTION OF HIGH VOLTAGE RADIATION AND MATTER

1. Absorption

To appreciate a number of points of importance in gamma ray therapy, in particular the way in which biological effects are produced by high voltage radiation (X- and gamma radiation), and the foundations on which the most satisfactory system of dosage available at the present time is built, it is necessary to consider the processes by which energy is absorbed from a beam of radiation, by material through which the radiation passes. We are concerned with the manner in which energy, in the form of radiation, is lost to the beam within the material, and we shall see that this occurs in the generation of moving electrons produced in one way or another by the radiation. These electrons, in their passage through the material, bring about ionization of the material. There seems little doubt that the effects produced by high voltage radiation, in biological material on which it falls, must be due to these moving electrons and the ionization they produce. The measurement of the ionization when the material ionized is air, forms the basis of the measurement of radiation dose.

2. Absorption of High-voltage Radiation

In its passage through matter a beam of monochromatic high-voltage radiation is absorbed according to an exponential law, so that if I_0 is the incident intensity of radiation and I is the intensity after passing through a thickness d of a material, we may write :—

$$I = I_0 e^{-\mu d} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where μ is a constant for the material and is called the *total linear absorption coefficient* for the radiation in question. This constant represents the total absorption that occurs and may be regarded as that fraction of the energy of the beam which is removed per unit volume of the material it traverses.

The total absorption represented by the coefficient μ is actually made up of two separate physical processes known as *photo-electric absorption* and *scattering absorption.* There is a linear absorption coefficient which represents each of these processes, a coefficient written as τ for photo-electric absorption and σ for scattering absorption. It follows that $\mu = \sigma + \tau$. There is a third absorption process, nuclear absorption, but this is of no significance in the present problems of radio-therapy and will not be considered.

In the process of photo-electric absorption, the radiation, if of sufficiently short wave-length, removes orbital electrons from the atoms of the material and imparts a velocity to them. Following the ejection of such an electron, a rearrangement of the electrons takes place within the atom from which it came, and this rearrangement gives rise to electromagnetic radiation of a wave-length characteristic of the emitting atom (fluorescent radiation). The electrons ejected in this process are *photo-electrons.* The process is explained by the quantum theory upon the assumption that the whole energy of the incident quantum of radiation is used, part to extract the photo-electron from the atom, and the remainder to impart to the electron its velocity. Thus the process is written as :—

$$h\nu = \mathrm{W} + \frac{1}{2}m\mathrm{v}^2 \quad . \quad . \quad . \quad . \quad (1)$$

where ν is the frequency of the incident radiation,

h is Planck's constant ($6{\cdot}556 \times 10^{-27}$ erg. seconds),

W is the energy required for the extraction process,

m is the electronic mass and v the velocity acquired by the electron so that $\frac{1}{2}m\mathrm{v}^2$ is the kinetic energy of the electron.

For very short wave-lengths such as those of gamma radiation, W is almost negligible and the relation is practically $h\nu = \frac{1}{2}m\mathrm{v}^2$.

This process represents the transference of energy from the form of primary electromagnetic radiation to the form of secondary corpuscular radiation and for this reason it is often referred to as true absorption.

Scattering absorption is absorption that takes place when the radiation is scattered by the material so that the radiation changes its direction. It is known that the scattered radiation is of two distinct kinds which are usually referred to as *truly scattered radiation* and *absorption-scattered radiation.*

Truly scattered radiation differs from the primary radiation only in direction, having exactly the same wave-length. It is often referred to as unmodified radiation. In this process none of the energy of the primary beam is truly absorbed within the material, it is merely deflected.

Absorption scattered radiation is different from the truly scattered radiation in that it undergoes a change in wave-length as a result of the scattering process. Compton has shown that the process may be explained satisfactorily by means of the quantum theory as follows :—

The radiation is regarded as consisting of quanta or photons having specific energy and momentum. A quantum of radiation $h\nu$ is considered to strike a free electron so that the process may be described by equations representing the conservation of energy and momentum. Part of the energy of the original quantum is used up in giving the electron a recoil velocity v in the direction θ (see Fig. 12), while the remainder appears as a quantum of radiation $h\nu'$ of lower frequency ν', scattered in the direction ϕ. From the equations representing this process it may be shown that the actual change in wave-length $\delta\lambda$ that occurs is :—

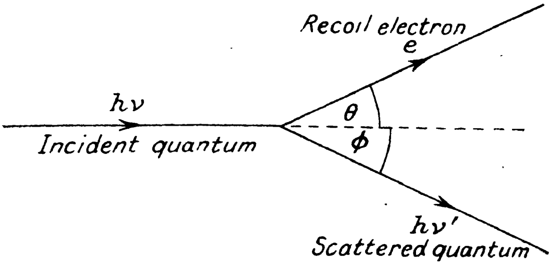

FIG. 12.—Illustrating the Compton scattering of a photon $h\nu$ which results in a photon of lower energy $h\nu'$ at an angle ϕ and a recoil electron at an angle θ.

$$\delta\lambda = \frac{h}{mc}(1 - \cos\phi) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where c is the velocity of light.

The kinetic energy E of the *recoil electron* is given by :—

$$E = h\nu . \frac{2\alpha \cos^2\theta}{(1+\alpha)^2 - \alpha^2 \cos^2\theta} \quad . \quad . \quad . \quad . \quad (3)$$

where $\alpha = \frac{h\nu}{mc^2} = \frac{0{\cdot}0243}{\lambda}$, λ being the original wave-length of the radiation in A.U. and, of course, equal to $\frac{c}{\nu}$.

From equation (2) it is found that the maximum change in wave-length occurs when the radiation is scattered at $\phi = 180°$, *i.e.*, in a direction opposing that of the original radiation. By putting in the values of the constants this maximum change is seen to be 0·0486 A.U. or 48·6X.U. (1X.U. $= 10^{-11}$ cm.). Similarly equation (3) shows that recoil electrons may be generated having kinetic energies which are varying fractions (depending upon θ) of the incident quantum. Thus energy is truly absorbed from the radiation by this process which has the same type of end results, viz., moving particles, as has the process of photo-electric absorption.

It is customary to represent the magnitudes of the truly scattered radiation and the absorption scattered radiation by the linear coefficients σ_s and σ_a respectively, *i.e.*, $\sigma = \sigma_s + \sigma_a$ and $\mu = \tau + \sigma_s + \sigma_a$.

We see that the energy which is truly absorbed, in the sense that it gives rise to energy of another form (moving electrons), is represented by $\tau + \sigma_a$. It is this energy which must be responsible for any effects which the radiation produces in the material such as ionization and biological effect.

3. Dependence of the Absorption Processes upon the Material of the Absorber and the Wave-length of the Radiation

As a general rule, the total absorption of radiation increases with the atomic number of the absorbing material and with increasing wave-length of the radiation.

The most recent work[1,2] with short wave-length radiation appears to show that the photo-electric absorption is proportional to the fourth power of the atomic number of the absorbing material, so that photo-electric absorption becomes more and more important as the atomic number of the material increases.

For the longer, X-ray wave-lengths, photo-electric absorption is found to be proportional to the cube of the wave-length of the radiation, but for gamma ray wave-lengths it seems to be more nearly proportional to a power of the wave-length equal to 2·2.

More accurate investigations of the subject have been made by Read[1] and Gray[3] but the important fact at this moment is that photo-electric absorption decreases rapidly with decrease of wave-length.

As a result of the relation of photo-electric absorption with atomic number and wave-length, the photo-electric absorption of gamma radiation by light atom materials is very small and tends to become negligible for the shortest wave-lengths. It follows that very little of the absorption of gamma rays in tissues occurs because of the production of photo-electrons.

The scattering of high-voltage radiation is due to the interaction of the radiation with the electrons in the material and theoretical[4] and experimental[5] [6] [7] [8] work on the subject has shown that all electrons scatter equally, whatever their state of binding in the atom. If the scattering per electron is known for a specific wave-length of radiation, the scattering per c.c. of the material can be calculated from a knowledge of the number of electrons per c.c. of the material.

The dependence of the scattering absorption coefficients upon wave-length in the radium gamma ray range of wave-lengths is shown in Fig. 13. The values of the coefficients given are those

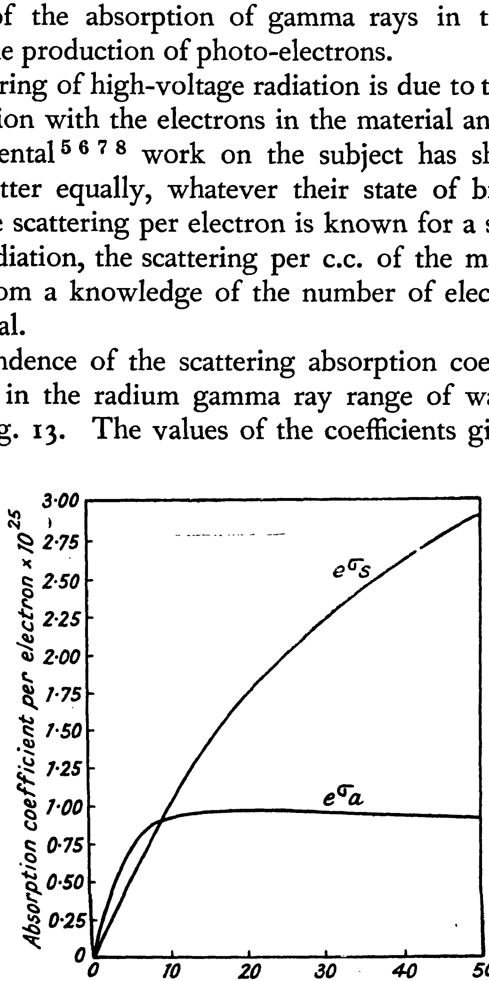

FIG. 13.—Variation of the scattering coefficient $e^{\sigma}s$ and the scattering absorption coefficient $e^{\sigma}a$ with wave-length according to the Klein-Nishina formulæ.

calculated per electron of material. They have been calculated by means of the Klein-Nishina formulæ[4] which were deduced to explain the phenomena of scattering and do so remarkably well. When the absorption coefficients are expressed per electron they are written as ${}_e\sigma_a$ and ${}_e\sigma_s$ for the absorption scattered and truly scattered radiations respectively. Similarly ${}_e\tau$ represents the photo-electric absorption coefficient per electron.

It is seen that ${}_e\sigma_a$, which represents the energy truly absorbed in the scattering process, remains sensibly constant over the whole of the radium B spectrum (35 X.U. to 51 X.U.) and part of the radium C spectrum and only varies very slowly over the remainder of the radium C spectrum.

4. The Absorption of Gamma Radiation in Air and "Tissue-like" Substances

In gamma ray therapy we are particularly concerned with the absorption processes in air and in " tissue-like " substances. With the former because, as we shall see later, it is upon the effects produced by the radiation in air that the most satisfactory method of dosage has been based, and with the latter with a view to obtaining more detailed physical information concerning the biological effects produced by the radiation. We have seen that the true absorption of energy from the radiation by an absorbing medium is very largely dependent upon the atomic number of that medium. It may be shown[9] that the effective atomic number for air is 7·7, that of an average tissue is 7·5, while for water the effective atomic number is 7·4. Water and air, therefore, are comparable to tissue in atomic number so that effects produced by gamma radiation in air and water should be very nearly the same as those produced in tissue.

All the above materials are of low atomic weight and number so that absorption of gamma ray energy within them, will occur essentially by the production of recoil electrons, the photo-electric absorption being negligibly small for the short gamma ray wavelengths. If it were not for the phenomenon of " Compton-Scatter " with its generation of recoil electrons, no appreciable amount of energy would be absorbed when gamma radiation passes through tissues and presumably no biological effect would be produced by the radiation.

The comparable behaviour of air, water and tissue, in their interaction with gamma rays, is of the utmost practical value. Thus the ionization of air provides a means of measuring a quantity which is, to a close approximation, proportional to the ionization produced in tissue[10] and this measurement is made the basis of the ionization method of gamma ray dosage.

Again, we are often concerned to examine the distribution of radiation that exists, throughout a bulk of tissues, when gamma ray sources are applied externally to or within the tissues. This would not be an easy matter to achieve experimentally, but the fact that water is " tissue-like " in its behaviour with respect to gamma rays enables us to use a " water-phantom " within which we may make our measurements with much less difficulty.

The distances traversed by the recoil electrons produced in the scatter absorption process are of some interest as will be seen later. The maximum range of the recoil electrons generated by the mean wave-length of the radium gamma rays used in therapy (approx. 20 X.U.) is of the order of 5 mm. in water or tissue. Those electrons with this maximum range are ejected forward in the direction of the radiation which excites them.

To a first approximation, the ranges in air and water are inversely proportional to their densities, so that the ranges of the recoil electrons in air are some 770 times as great as in water. Thus, the maximum ranges of the recoil electrons in air will be of the order of 4 metres (in the forward direction) for a mean wave-length of 20 X.U. These facts will be seen to be of great importance when we consider the ionization method of measuring gamma rays (Chap. III).

5. Absorption of Gamma Rays in Primary Screenage Materials

In practical radium therapy constant use is made of the heavy elements because they are the most effective absorbers and filters for gamma radiation. For purposes of protection or filtration (especially in radium teletherapy), lead is commonly used, because, besides being a good absorber of gamma rays, it is relatively cheap. Recently an alloy of tungsten[11] has been developed for the purpose of providing more compact protection in radium teletherapy. This alloy * has a density of 16·5 grams per c.c., whereas the density

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* Details of this alloy may be found in the G.E.C. Leaflet No. 9368, which is a reprint of an article, " G.E.C. Heavy Alloy, Its Production Properties and Uses," by G. H. S. Price, S. V. Williams and G. J. O. Garrard, *G.E.C. Journal*, Vol. XVI, No. 4, August, 1941.

of lead is 11·4 grams per c.c. For screenage or filtration purposes, as in the design of radium needles, tubes, etc., platinum (density 21·5 grams per c.c.) is most widely used, although in some instances gold (density 19·3 grams per c.c.) takes its place. The high densities of the last two materials make them extremely efficient absorbers of gamma rays. It is because of this that platinum is so useful for the construction of radium needles, since one is able to keep the diameter of a needle at a minimum value and yet provide for the absorption of the primary beta rays and soft gamma rays from the radium within. It is obvious that the absorption of gamma radiation in these dense materials is a matter of importance.

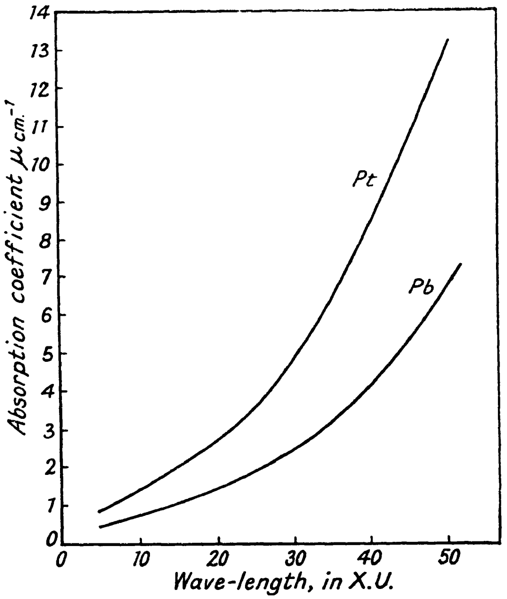

FIG. 14.—Relation between the linear absorption coefficients of lead and platinum and the wave-length of the radiation.

In Fig. 14 curves are given which show the variation with wave-length of the linear absorption coefficient for lead and platinum. The wave-lengths considered cover the radium gamma ray spectrum and the values were obtained by a combination of the available experimental and theoretical data. Thus Read[1] has published values of the absorption coefficient in lead for wave-lengths between 21 X.U. and 51 X.U. From this data and other facts concerning the relationship between absorption coefficient, atomic number and wave-length, values were determined for lead at wave-lengths shorter than 20 X.U., and another complete curve was calculated for platinum.[12] It follows from Fig. 14 that the thicknesses of lead required to provide a certain absorption are approximately twice those of platinum.

The importance of photo-electric absorption in the case of the heavy elements, even for the shortest wave-lengths, may be seen from Table 4A, which gives the values of μ and τ for lead (as measured by Read[1]), over the region of wave-lengths 21 X.U. to 51 X.U. Even for 21 X.U. wave-length, more than half the total absorption is photo-electric and for 51 X.U. this has risen to more than 86 per cent.

TABLE 4A.—*The Absorption Coefficients in Lead for Wave-lengths between* 21 *and* 51 *X.U.* (*Read*[1])

Wave-length λ in X.U.	21	24	27	30	33	36	39	42	45	48	51
μ cm^{-1}	1·53	1·75	2·06	2·42	2·82	3·30	3·92	4·60	5·37	6·26	7·25
τ cm^{-1}	0·827	1·01	1·28	1·60	1·97	2·42	3·00	3·67	4·43	5·29	6·25

The exact specification of absorption coefficients for these materials is difficult, because the values naturally depend upon the initial filtration of the radium gamma rays, that is, upon the initial effective wave-length of the gamma radiation. For fairly light screenage, as is usually met with in practice, it is customary to use a value of 2·0 cm.$^{-1}$ for the absorption coefficient of platinum, and, in view of the very slight difference in atomic number and density of gold and platinum, the same value suffices for calculations of the absorption in gold. *

With regard to the alloy of tungsten, Grimmett and Read[13] have compared the absorption within this alloy with that in lead, and found that when the percentage of radiation transmitted was plotted against mass per square cm. of absorber, the results for the alloy and lead fell on the same curve. After passing through a thickness of material equivalent to 1·76 cm. of lead, the absorption coefficient of lead corresponded to 0·58 cm.$^{-1}$ and that of the alloy to 0·87 cm.$^{-1}$. The absorption coefficient in this alloy may therefore be determined quite satisfactorily from the absorption coefficient in lead, on the assumption of proportionality with density.

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* Dr. G. J. Neary has recently determined a value of μ = 1·48 cm.$^{-1}$ as the mean linear *true* absorption coefficient for platinum at a filtration of 0·5 mm. Pt. (*British Journal Rad.*, Vol. 16, 1943, p. 263).

For general practical application of the results, it is convenient to use the approximate data summarised in Table 5 when one is

TABLE 5.—*Effect of increasing the Screenage of a Radium Source beyond* 0·5 *mm. Platinum*

Added thickness of platinum in mm.	Percentage of gamma radiation absorbed
0·3	5·8
0·5	9·5
1·0	19·1
1·5	25·9

Gold . . .	As platinum.
Tungsten alloy .	As three-quarters of its thickness of platinum.
Lead and silver .	As one-half their thickness of platinum.
Monel and brass .	As one-third their thickness of platinum.

TABLE 6.—*Absorption of Gamma Radiation in considerable thickness of Lead and Tungsten Alloy*

Thickness of lead in cm.	Percentage of gamma radiation absorbed
1	44·0
2	68·6
3	82·4
4	90·2
5	94·5
8	99·05
10	99·70
15	99·98

Tungsten alloy is equivalent to 1·5 times its thickness of lead.

concerned with the changes in radiation emission that occur as a result of change in the filtration of the source. This table shows the percentage of gamma radiation that is absorbed when the filtration is increased by specific thicknesses of platinum. In addition, the relation of other commonly used metals is given to a sufficient accuracy for everyday use. It is assumed that the source is initially screened by a thickness of 0·5 mm. of platinum.

Similar approximate data for the percentage absorption of gamma radiation in lead and tungsten alloy, which is of value when the protection of personnel by considerable thicknesses of these materials has to be considered, is given in Table 6.

6. The "Effective Wave-length" of Radium Gamma Rays

Knowledge of the mean wave-length of the gamma rays of radium and its dependence upon the primary filtration of the radium is of value in radium therapy, when it is desired to know the quality of the primary radiation that is used and the possible advantages of increased filtration.

One method of obtaining information with regard to how the "effective wave-length" of the gamma rays of radium depends upon the thickness of lead filtration, is by means of a curve relating lead filtration to the absorption coefficient in aluminium, of the gamma rays emerging through the filtration. Such a curve has been given by Rutherford, Chadwick and Ellis,[25] representing the data of many workers. By an application of this curve and the Klein Nishina formulæ,[4] it is possible to calculate how the effective wave-length of the radiation depends on the lead filtration.

A simpler method has been used by Mayneord[12] which has the advantage of being more immediately applicable to other filter materials in addition to lead. It makes use of the data concerning the gamma ray spectrum which was given in Chapter I and absorption data such as that given for lead and platinum in Fig. 14.

The curves shown in Figs. 15 and 16 were obtained by these methods. Fig. 15 shows the relation between the effective wave-length of the radium gamma rays and the lead filtration applied to the radium as deduced by both methods. The two methods do not agree exactly, but considering the nature of the data used, the discrepancy is not great. It is likely that the values obtained by the second method (curve B) are more near to the actual facts. Fig. 16 gives a similar curve for platinum filtration which was deduced by the second method.

Other, lighter materials, such as copper, are sometimes used as primary filters, but it has been shown [12] that such materials transmit the longer wave-length radiations of the gamma ray spectrum more readily than do equivalent thicknesses of lead and platinum and so do not harden the radiation so effectively. It is therefore preferable to use the heavy elements platinum, lead or tungsten alloy, as the

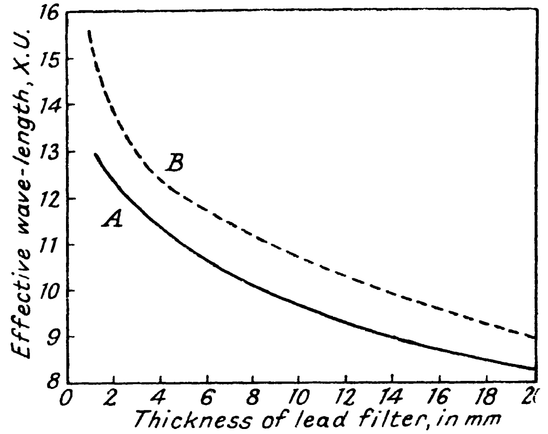

FIG. 15.—Effective wave-length of radium gamma rays as a function of lead filtration.

A. First method. *B*. Second method.

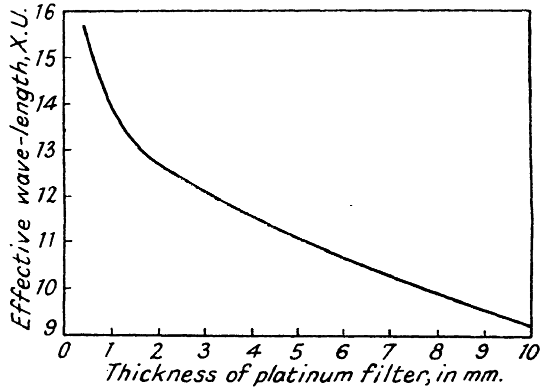

FIG. 16.—Effective wave-length of radium gamma rays as a function of platinum filtration.

material for primary filtration if it is required that the radiation should have the maximum possible penetration.

It may be seen from Figs. 15 and 16 that increasing the filtration of radium beyond 2 mm. of platinum, or its equivalent in lead, does not rapidly shorten the effective wave-length of the gamma radiation. It follows that in the therapeutic use of radium, no great advantage in penetration of the radiation is obtained by using filtration in excess of 2 mm. platinum. This is especially seen to be the case when one considers that in actual working conditions, the effective wave-lengths are, as we shall see later, considerably increased because of the presence of softer radiations scattered by the tissues. The main effect of the extra filtration would be to absorb and waste useful radiation.

7. Secondary (Beta) Radiations from Filter Materials

We have seen that radium sources used for gamma ray therapy are enclosed in a sufficient thickness of metallic filter to remove all primary beta rays and the softer gamma rays. The gamma rays, however, in their interaction with the filter, give rise to secondary beta rays (the photo-electrons and recoil electrons from the filter). It is important, therefore, to be aware of the physical properties and biological possibilities of these secondary radiations. For this reason they have been the subject of many investigations of which we shall mention only a few. The work that is referred to contains full reference to the other investigations that have been made.

It is generally agreed that for the secondary radiation emerging in the same direction as the primary gamma radiation, the so-called " emergence emission," a decidedly minimum quantity is found for elements of medium atomic number (between $Z = 25$ and $Z = 50$, so that copper, nickel, zinc, palladium, etc., are included). For secondary radiation that emerges on the same side of the filter as the source, the so-called "incidence emission," the amount increases continuously with increase of the atomic number of the filter.

A recent paper by Quimby, Marinelli and Blady[14] gives a review of the most important work in connection with this subject and describes further experiments carried out with conditions closely comparable to those of interstitial or intra-cavitary radium therapy. Fig. 17 shows the results obtained by these workers from measurements made of the secondary emergence radiations from the complete surface of a tubular source, when the surface was covered by various filtering materials. The curve shown expresses how the actual amount of secondary emergence emission varies with the atomic number of the filter material.

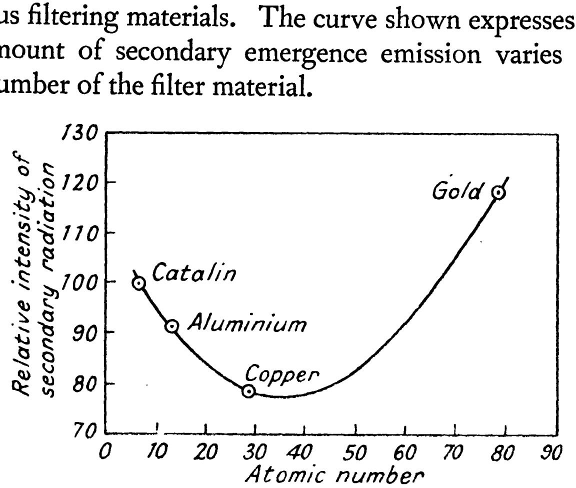

FIG. 17.—Curve showing relation between atomic number of radiator and secondary radiation. (*Quimby and Others.*)

Fig. 18 shows the dependence of the emergence and incidence emissions upon atomic number as measured by Wilson[15] very recently for sheets of various materials through which gamma radiation was passed. In this case the change in amount of secondary emission was made manifest by comparing the ionization in a chamber, when one wall was of the material concerned, with that

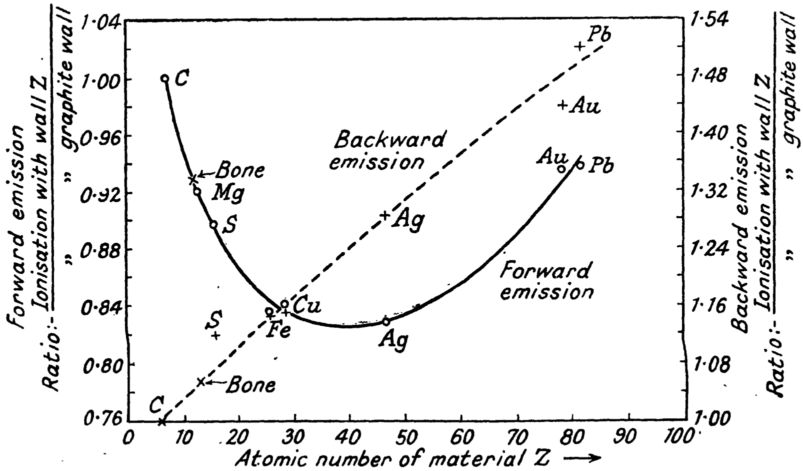

FIG. 18.—Relation between the atomic number and the measured ionizations for emergence and incidence emissions. (*Wilson.*)

when the wall was of graphite. Figs. 17 and 18 both show the general characteristics described.

The results shown in Fig. 18 have an additional interest in that human bone was included among the materials examined; it is seen, that in so far as the emission of secondary radiations is concerned, bone is comparable to magnesium and appears to have an effective atomic number of about 12.

A number of workers have examined the absorption of the secondary beta rays in light materials comparable to tissues, and it is agreed that they are of low penetrating power, the greater part being absorbed in the first millimetre or so of tissue. Thus any therapeutic effect they may produce will be superficial and localised.

Many biological experiments have been concerned with this same problem, and although some deny the biological significance of the secondary rays, the majority have found that their effects must be taken into account. Mottram,[16] for example, showed that the emergence secondary radiation from lead was able to affect the number of takes of tumour fragments implanted into rats. Benner and Snellman[17] showed that the skin reaction due to radium applicators was more severe when the outer filter was of platinum than when it was of palladium ($Z = 46$). Recently Quimby and her co-workers[14] have confirmed these findings with skin erythema tests: they conclude that intra-cavitary applicators should be enclosed in a substance of intermediate atomic number such as stainless steel, nickel or silver, if the local reaction due to secondary beta-rays is to be kept to a minimum. It is often the custom in actual intra-cavitary radium therapy to cover the radium source with a thin covering of rubber. Such a covering produces less secondary beta radiation than the primary heavy metal filter, but it gives rise to slightly more than do the materials of intermediate atomic number.

Secondary beta radiation is also of great importance in radium teletherapy. In this case large areas of high atomic number materials are exposed to gamma rays and these materials might be applied perchance, directly to the skin, where it is particularly wished to keep the biological effects to a minimum, in order that as much treatment as possible may be given. To ensure that a minimum of secondary radiation reaches the skin areas through which treatment is given, it is essential to have a secondary filter of a medium atomic number material covering the aperture of the teletherapy unit. At Westminster Hospital brass sheet 1 mm. thick is used. The presence of large quantities of secondary radiation, and its removal by a copper secondary filter, is well illustrated by some results published by Flint and Wilson[18] which are shown in Fig. 19. The curve shows how the ionization measured at the aperture of a mass radium unit varied with the thickness of copper sheet placed between the aperture and the ionization chamber. The latter had walls of elektron metal (see Chap. III) 1 mm. thick. The first rapid fall in ionization with the initial increase in thickness of copper, is due to absorption of secondary beta radiations from the metal (gold and lead) of the unit. The slow, approximately linear fall, with further increase in copper thickness, represents absorption of gamma radiation. By extrapolating the linear curve back to zero thickness of copper it is seen that some 16 per cent. of the ionization measured for this condition was due to secondary beta radiation. It was completely absorbed by 1 mm. thickness of copper. In this same connection, we shall see in the next chapter, that if it is desired to measure doses of gamma rays given to the skin in terms of the röntgen, other considerations arise, and it may not be best to use secondary filters of intermediate atomic number in teletherapy; a secondary filter of a light "tissue-like" substance such as dense wood, wax, etc., of at least 4 mm. thickness, may then be preferable.

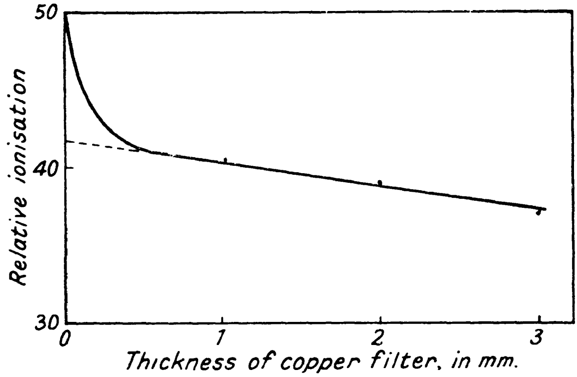

FIG. 19.—Absorption in copper of secondary radiations from aperture of a radium teletherapy unit. (*Flint and Wilson.*)

In general, it may be said, that if it is desired that effects on the skin be kept to a minimum, a thickness of about 1 mm. of copper or brass sheet should be between the skin and the radium source; the copper or brass should preferably be in contact with the skin. If, however, a purely superficial lesion is being treated, the secondary beta rays from the primary filter would probably be useful and a secondary filter may not be essential.

8. Effects of Scattering in Radium Therapy

The effects produced in radium therapy by the scattering of gamma rays in tissue or tissue-equivalent materials may be considered from two viewpoints, (*a*) with regard to the quantity of scattered radiation as compared with that of the primary radiation, and (*b*) with regard to the quality or wave-length of the scattered radiation and the effect of this upon the mean wave-length of all the radiations, primary and scattered.

(*a*) Amount of Scattered Radiation. From the general account that has been given of the absorption processes, and particularly by reference to Fig. 13, showing the variation of the scattering coefficients with wave-length, it will be seen that although practically the whole of gamma ray absorption takes place by scattering, nevertheless, the shorter the wave-lengths involved, the smaller is the total amount of scattering as represented by ${}_e\sigma$. The total radiation that reaches a depth in tissue when a beam of radiation is applied to that tissue, is comprised of the primary radiation that penetrates to that depth, plus the radiation scattered by the tissue medium to the point considered. It is known that in the case of X-rays the scattered portion may be a very considerable fraction of the total. We see, however, that for the shorter wave-length gamma rays, although the penetration is greater than for X-rays, so that a greater proportion of primary radiation will reach a depth in tissue, we must expect a smaller proportion of scattered radiation. Hence it cannot be expected that the total radiation reaching a depth will increase as rapidly as the increase in actual penetration of the radiation. This is borne out in practice for certain depths that are of importance in therapy.

A number of workers have investigated the amount of scattered gamma radiation that is present under a variety of conditions which approximate those arising in practical radium therapy. As a check and extension of experiments done by Bruzau,[19] Griffith [20] made measurements of the gamma ray intensity due to a radium source within water phantoms (tanks of water) of two different sizes. He used ionization chambers of light atom materials so that true measures of the gamma radiation were obtained. Some of his results are shown in Fig. 20 in which the measurements in water are compared with those made in air. When the measurements in water are identical

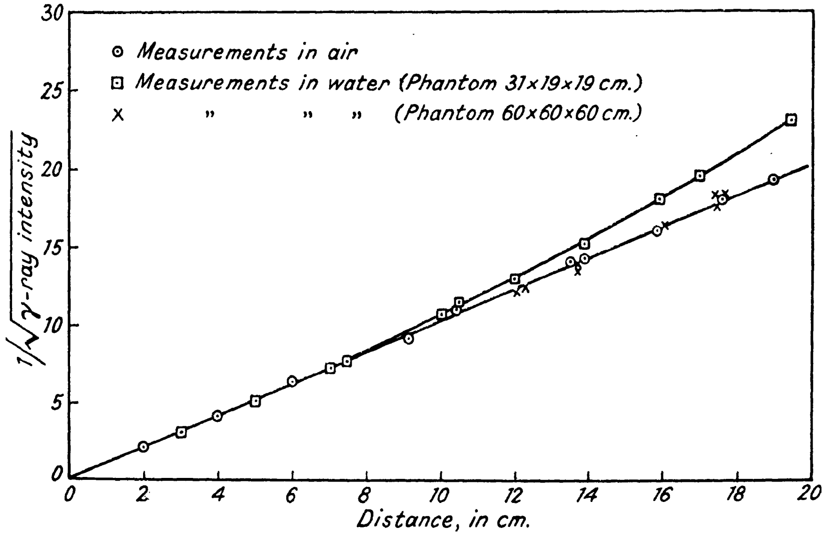

FIG. 20.—Comparison of gamma ray intensities measured in water with those in air. The straight line relation for the air measurements is an expression of the inverse square law. (*Griffith.*)

with those in air it means that the radiation absorbed by the water, between the source and point of measurement, must be compensated by scattered radiation from the whole of the water medium. The curves show that this equivalence is maintained for greater distances with the large phantom than with the small phantom, the larger bulk of scattering medium giving rise to more scattered radiation. It is clear from these results that for most of the conditions met with in clinical practice, the intensities around radium needles buried in tissues are little different from the intensities at the same points in air. This fact is of value when one wishes to study the intensity distribution due to an arrangement of radium sources.

Wilson [21] has examined the amount of scattered radiation present at various depths in a water phantom irradiated with a beam of gamma rays from a 2 gram radium unit. The aperture of this unit was only 3·5 cm. in diameter and its effective radiation diameter was not much greater. Fig. 21 shows the result of the comparison made in this case between the intensity in air and that in water at various depths from the surface to which the radiation was applied.

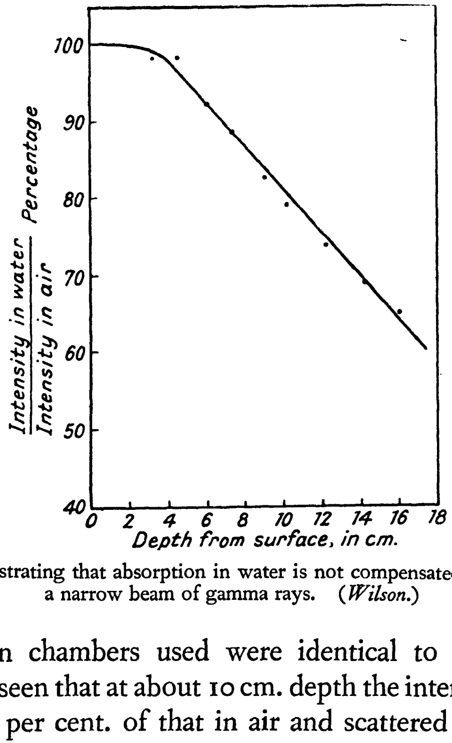

FIG. 21.—Illustrating that absorption in water is not compensated by scatter for a narrow beam of gamma rays. (*Wilson.*)

The ionization chambers used were identical to those used by Griffith. It is seen that at about 10 cm. depth the intensity in water is only some 80 per cent. of that in air and scattered radiation from the medium does not compensate for the radiation absorbed when only a narrow beam is considered. Wilson also showed that although the scattered radiation did not compensate for the absorption, nevertheless, some 16 per cent. of the radiation measured at about 10 cm. depth was scattered radiation. At smaller depths the percentage was smaller. At the surface of the water phantom to which the radiation was applied the amount of radiation " backscattered " was less than 5 per cent. of the total.

Mayneord and Honeyburne[22] confirmed these findings in a more general study of the radiation intensity at depths in a water phantom when it is irradiated by a narrow beam of gamma rays. They showed that the absorption that occurs may be described by an " Apparent absorption coefficient " $\mu' = 0{\cdot}025$ cm.$^{-1}$. They showed also that the back-scattered radiation at the surface increases with increase in distance between the surface and the source of radium, but is not at any time as great as in the case of X-rays.

(*b*) QUALITY OF SCATTERED RADIATION. We have seen that the scattering process, whereby energy is truly absorbed from gamma radiation, also involves a process in which the wave-length of the radiation is increased. The magnitude of this change in a single scattering process depends upon the angle ϕ at which the radiation is scattered, being given by $\frac{h}{mc}(1 - \cos\phi) = 24{\cdot}3\,(1 - \cos\phi)$ X.U. (see Fig. 12). The maximum possible increase occurs when the scattered ray is in the opposite direction to the primary ray, in which case $\phi = 180^\circ$ and the increase in wave-length is 48·6 X.U. When we consider that the effective wave-length of the gamma radiation used therapeutically is only of the order of 15 X.U. this change is considerable, and, in view of the amount of scattered radiation present, it is to be expected that the wave-lengths of the radiations within tissues irradiated by gamma rays, will be markedly greater than that of the primary radiation itself. This is especially so when one remembers that in practice multiple scattering will occur. Accurate investigation of this question is very difficult because of the short wave-lengths involved. Some information, however, is available, which at least indicates the order of magnitude of the wave-length changes that occur in therapeutic practice.

Experiments described by Bruzau[19] formed one of the earliest attempts to investigate the wave-lengths present in a " tissue-like " medium (water) when it is irradiated with gamma radiation. These experiments indicated the presence of scattered radiations softer than the primary radiation and suggested the order of magnitude of the wave-lengths present but lack of reliable absorption data hindered their interpretation. Rees and Clark[23] examined the quality of the scattered radiations present in a water medium irradiated by gamma radiation and their results appeared to show that wave-lengths were present which corresponded to multiple scattering.

More work has been done on this subject quite recently by Wilson[24] who used the ratio of the ionizations recorded in small ionization chambers of different wall materials, as an index of the wave-length of the radiations producing the ionizations. The method was made possible by the development of the theory of the small ionization chamber (see Chap. III) and the absorption data for short wave-lengths that are now available. If approximately monochromatic radiations of wave-lengths between 15 and 50 X.U. had been available for purposes of "calibration" more reliable data could have been obtained. These experiments were an attempt to examine the effective wave-length of the total radiation (primary and scattered) present under conditions which correspond closely to those of therapeutic practice, namely, irradiation with a radium teletherapy unit, surface irradiation as with surface applicators and interstitial irradiation. The results obtained for these conditions are shown in Figs. 22, 23 and 24 respectively, being expressed more directly than they were in the original paper.

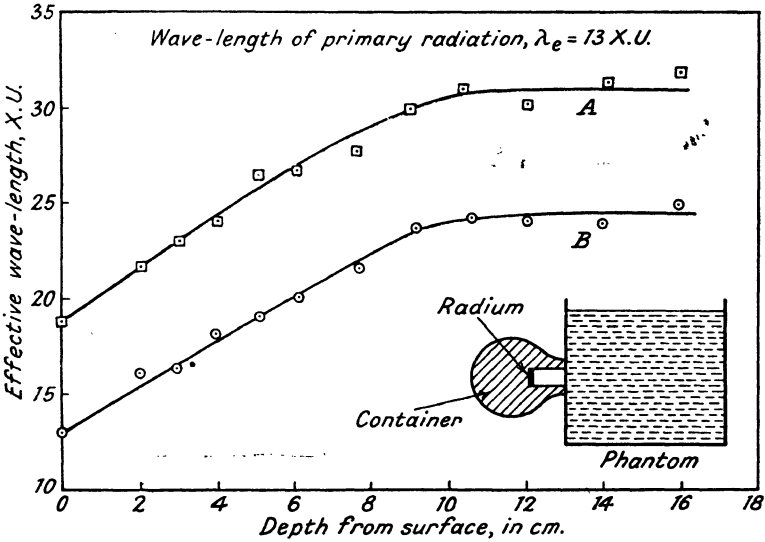

FIG. 22.—Effective wave-length of the depth radiations from a mass radium unit. (*Wilson.*)
(*A*) Field 9 cm. diameter.
(*B*) Field 3·5 cm. diameter.

Fig. 22 shows how the effective wave-length of the radiations within a water phantom irradiated by means of a mass radium unit (see inset diagram), varies with the depth from the surface. Curve A is for an aperture 9 cm. in diameter and curve B for another

3·5 cm. in diameter. It is seen that the depth radiations for the larger aperture are always softer at corresponding points than those for the smaller field. This is no doubt due to the much greater bulk of medium that is irradiated in the former case, giving rise to more scattered radiation. The surface radiations for the larger field have a greater effective wave-length (19 X.U.) than those for the smaller field, the wave-length of which is the same as that for the primary radiation (13 X.U.). The maximum effective wave-length found was 30 X.U. at 10 cm. depth for the 9 cm. diameter aperture.

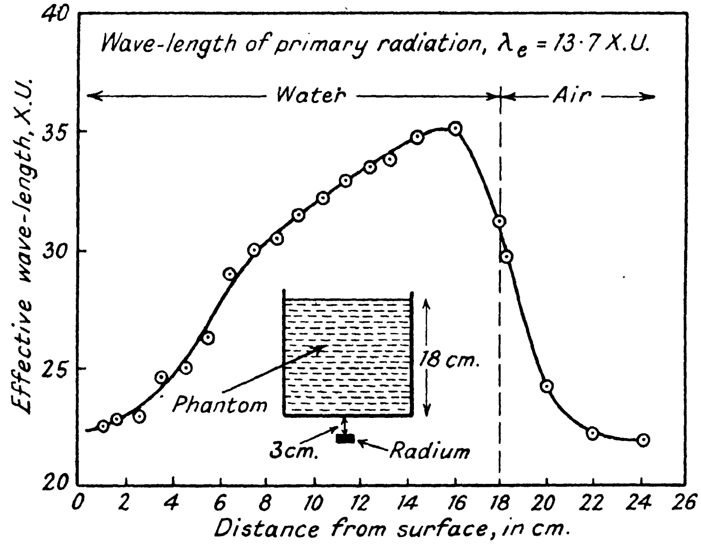

FIG. 23.—Effective wave-lengths of radiations from an "open" source applied near the surface. (*Wilson.*)

This is nearly two and a half times as great as that of the primary radiation. For both fields the quality does not change after a depth of about 10 cm. It appears that some sort of equilibrium is reached at this depth.

Fig. 23 shows the results obtained in the case of surface irradiation with an open source of radium. These conditions approximate those of treatment with surface applicators (see inset Fig. 23). The estimated primary effective wave-length in this case was 13·7 X.U. It is seen from Fig. 23 that the hardest radiation present in the water phantom, that at the surface, has an effective wave-length as great as 22 X.U. and at about 15 cm. depth this has increased to 35 X.U. The sharp decrease in wave-length after a depth of about 17 cm. is due to the change in medium from water to air as indicated in Fig. 23.

When a radium source was used embedded completely within the water medium so as to correspond to the case of interstitial therapy, the results shown in Fig. 24 were obtained, the effective wave-length being measured at various distances from the radium source. The hardest radiation measured in this case had an effective wave-length of 25 X.U., although that of the primary radiation from the source itself was only 14 X.U. The maximum effective wave-length was of the order of 35 X.U.

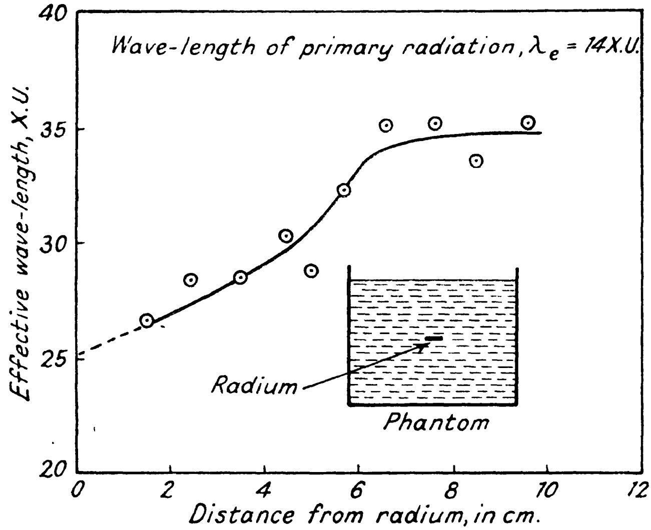

FIG. 24.—Effective wave-lengths of radiations from a source buried "interstitially." (*Wilson.*)

Thus it is seen that the wave-lengths of the radiations used in the various therapeutic methods are considerably greater than that of the primary gamma radiation itself and in view of the fact that these results are for the total radiation, it is highly probable that the scattered radiations contain even longer wave-lengths, as was suggested by Rees and Clark.[23] This question merits further investigation. It is certain that if wave-length of radiation is a factor in its biological effect, it will eventually be as necessary to know the quality of the tissue radiations as it is to know the quantity absorbed.

One point is clear, namely, that in the actual practice of the various techniques of radium treatment. the wave-lengths used are considerably longer than those of the primary radiations which originate from the source.

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CHAPTER III

GAMMA RAY DOSIMETRY-METHODS AND THEORY

A NUMBER of methods have been used in an endeavour to express the " dose " in radium gamma ray therapy. Some of these methods have only a remote connection with what is strictly meant by dose, and unfortunately they are still used very frequently as though they are of real value and sufficient in themselves. Although the present position could not be described as perfect, we are able now to measure doses of gamma radiation in terms which bear a definite relation to the energy absorbed by the tissues from the radiation. It should be the constant endeavour of everyone who uses radium therapeutically, to determine the doses used, by the methods which we shall see are available at the present time.

1. " Milligram-hours " and " Millicuries destroyed."

The earliest attempt to express dose was in terms of either milligram-hours or millicuries destroyed, that is, as the product of the number of milligrams of radium and the hours for which it was applied, or as the number of millicuries of radon destroyed during the treatment period. A relation between the two quantities (p. 9, Chap. I) is that from the point of view of radiation emitted, 1 millicurie destroyed is equivalent to 132·4 milligram-hours.

It is fairly obvious that these so-called units of dose tell one nothing except the period of treatment and the quantity of radium or radon used. It is as useless to state a gamma ray dose in milligram-hours as it would be to describe an X-ray dose as so many milliampère-minutes. The number of milligram-hours is only one of the factors that determine the dose and itself serves only as a record of the work done by the radium.

If full details are available for any given radium distribution, such as number, filtration, length, strength and position of the sources, it is theoretically possible to determine the distribution of gamma radiation by mathematical calculation, although in practice it may be extremely tedious. This mathematical method is, however, of extreme value to radium therapy.

2. Mathematical Method of Radium Dosage.

This method is based upon the inverse square law of radiation. A unit of intensity is used rather than a unit of dose, so that unit intensity is defined as the intensity of gamma radiation at a distance of 1 cm. from a 1 mgm. point source of radium filtered by 0·5 mm. of platinum; at a distance d cm. from a point source of m mgm. the intensity is $m/_{d}2$. This is the natural unit for purposes of calculation. Sievert has suggested the name Intensity-millicurie (Imc.) for the unit. The dose delivered when an intensity of 1 Imc. is applied for 1 hour is then described as 1 Imc.-hour; this dose is also often referred to as 1 cm. mgm.-element-hour (1 cm. mgm.-el.-hr.), the filtration being understood.

In using this method no account is taken of secondary radiations from the radium containers or of scatter and absorption within the irradiated medium. Corrections that may be applied to allow for these factors will be referred to when necessary. Obviously, if the unit of intensity is determined in terms of some other unit, say by a measurement, then doses expressed in terms of the first unit may be transferred into the other. We shall see that this is what is often done in practice, provided certain conditions are fulfilled. Because of this and because of the extreme flexibility of mathematical calculation, this method proves itself invaluable for the arrangement of radium sources to provide specific distributions of radiation.

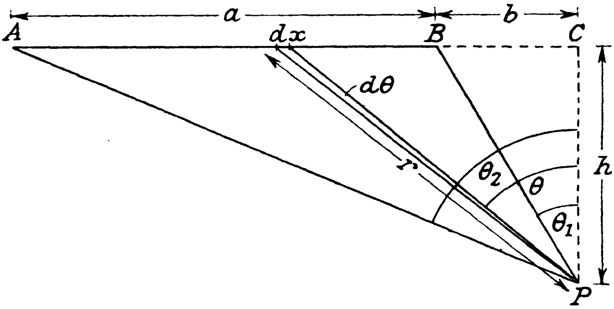

FIG. 25.—Calculation of intensity at P due to a straight line source AB.

Sievert[1, 2, 3, 4], Souttar,[5] Mayneord,[6] and others, have used the mathematical method to examine the distribution of intensity around various simple geometrical arrangements of radium. We may illustrate the procedure with advantage by considering a number of simple, but useful cases, taken from this literature.

(i) A STRAIGHT LINE SOURCE.[1, 6]

(*a*) *Unfiltered* (or filtration regarded as constant). Let the linear density of the source be ρ mgm. per cm. supposed constant along the source.

Then the total intensity I_p at the point P due to the whole source (see Fig. 25) is :—

$$I_p = \int_0^a \frac{\rho . dx}{r^2}$$

$$\text{but } dx . \cos\theta = r . d\theta \text{ or } dx = \frac{rd\theta}{\cos\theta} \text{ and } r = \frac{h}{\cos\theta}$$

$$\therefore I_p = \rho \int_{\theta_1}^{\theta_2} \frac{d\theta}{h} = \frac{\rho}{h}[\theta_2 - \theta_1] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$i.e., I_p = \rho \left[\frac{\text{Angle subtended by the line}}{\text{Perpendicular distance on to the line}}\right]$$

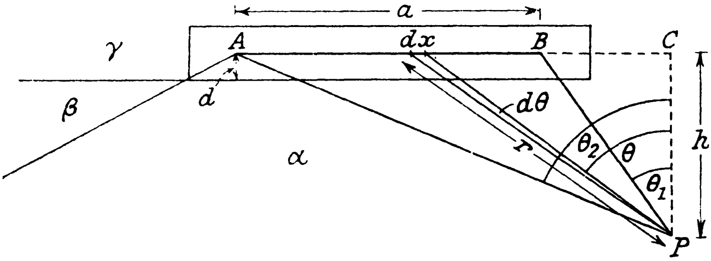

FIG. 26.—Calculation of intensity at P due to a filtered line source.

(*b*) *Filtered.*

In this case, for any point P in the region marked α (see Fig. 26) ; the intensity due to the element dx is equal to $\frac{\rho . dx}{r^2} . e^{-\frac{\mu d}{\cos\theta}}$ where d is the thickness and μ cm.$^{-1}$ the absorption coefficient of the filtering material. In this case then,

$$I_p = \frac{\rho}{h} \int_{\theta_1}^{\theta_2} e^{-\frac{\mu d}{\cos\theta}} . d\theta$$

$$= \frac{\rho}{h}\left[\int_0^{\theta_2} e^{-\frac{\mu d}{\cos\theta}} . d\theta - \int_0^{\theta_1} e^{-\frac{\mu d}{\cos\theta}} . d\theta\right] \quad . \quad . \quad . \quad . \quad (2)$$

Tables of integrals of the form given in equation (2) have been published by Sievert.[3,4] A number of those most pertinent to practical calculations are reproduced in Appendix II. The regions around the source marked β and γ require rather special treatment,[6] but in therapeutic practice we are seldom concerned with what occurs in these regions. Fig. 27 illustrates the results of such calculation for one of the 3 mgm. needles used at Westminster Hospital, the absorption coefficient of the platinum filter being taken as 2·0 cm.$^{-1}$. The curves show lines of equal intensity and are commonly referred to as isodose curves or dose contours.

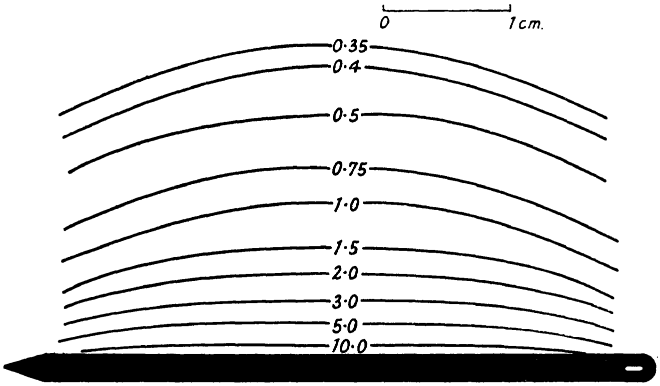

FIG. 27.—Calculated isodose curves around a 3 mgm. needle. Intensity expressed in Sievert units (Imc).

(ii) UNIFORM CIRCULAR RING OF RADIUM—FILTRATION REGARDED AS CONSTANT.[1,5,6]).

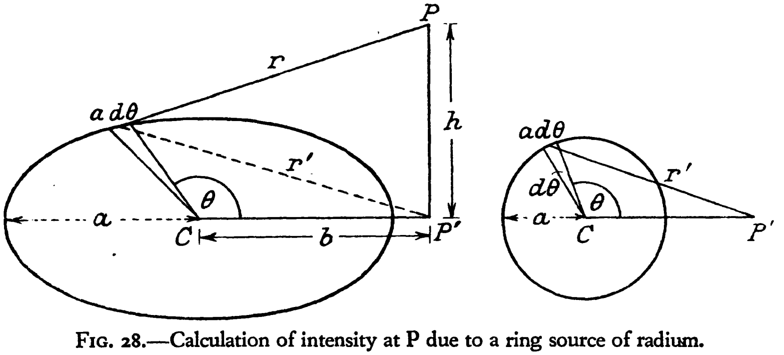

FIG. 28.—Calculation of intensity at P due to a ring source of radium.

ρ is the line density of the ring in mgm./cm. and a is its radius. Then in Fig. 28, the intensity at any point P due to an element of the ring of length ds $(= a.d\theta)$ is :—

$$\rho . \frac{a\,d\theta}{r^2} \text{ which equals } \frac{\rho a . d\theta}{a^2 + b^2 + h^2 - 2ab\cos\theta}$$

since $r^2 = r'^2 + h^2$ and $r'^2 = a^2 + b^2 - 2ab\cos\theta$

∴ The total intensity I_p at P, due to the whole ring, is :—

$$I_p = \rho \int_0^{2\pi} \frac{a . d\theta}{a^2 + b^2 + h^2 - 2ab\cos\theta}$$

$$= \frac{2\pi a \rho}{\{[a^2 + b^2 + h^2]^2 - 4a^2b^2\}^{\frac{1}{2}}} \quad . \quad . \quad . \quad (3)$$

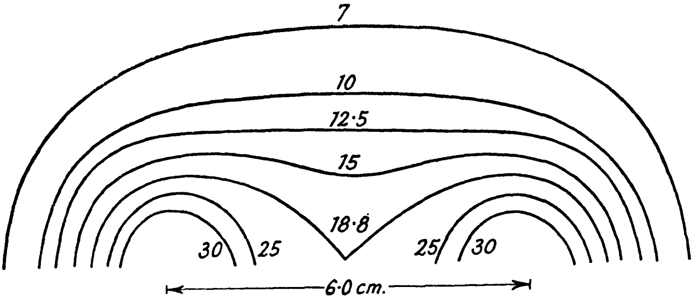

FIG. 29.—Dose contours around a ring source. $\rho = 1{\cdot}0$ mgm./cm. Intensities have been converted to r/hr. by a factor 1 Imc = 9 r/hr. $a = 3{\cdot}0$ cm. so that ring contains approx. 19 mgm. of radium. (*Mayneord.*)

Fig. 29 shows the type of radiation distribution that is indicated by application of equation (3). These isodose curves, taken from Mayneords' paper,[6] are calculated for a ring 3·0 cm. radius and line density 1·0 mgm./cm. It is seen that at distances greater than 1·5 cm. from the plane of the ring, the curves are very " flat." It

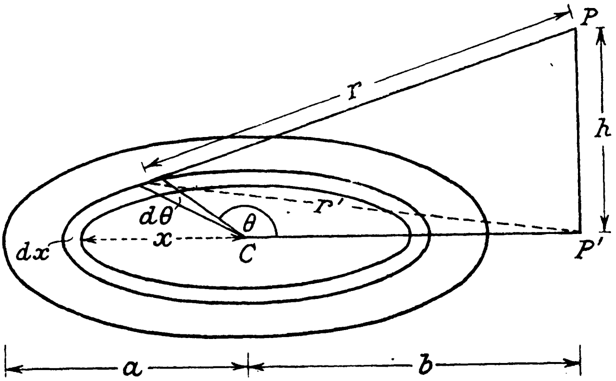

FIG. 30.—Calculation of intensity at P due to a thin circular disc of radium.

can be shown that the flattest curve, that is, the one that runs approximately parallel to the plane of the radium for a finite distance, is at a distance from the ring of $\frac{a}{\sqrt{2}}$ (approx. 0·7 a). This fact may be utilised in the construction of circular surface applicators (Chap. V).

(iii) CIRCULAR DISC OF RADIUM [6]

The intensity distribution around a circular disc source may be calculated by an extension of the calculation for a ring. Thus, if ρ is now the number of milligrams per square centimetre of the surface of the disc, the intensity at P due to the annulus of thickness dx and radius x (Fig. 30) is given by :—

$$\frac{2\pi\rho x\,.\,dx}{[(x^2+b^2+h^2)^2-4x^2b^2]^{\frac{1}{2}}}$$

so that the intensity I_p due to the whole disc is :—

$$I_p = \int_0^a \frac{2\pi\rho x\,.\,dx}{[(x^2+b^2+h^2)^2-4x^2b^2]^{\frac{1}{2}}}$$

$$= 2\pi\rho\int_0^a \frac{x\,.\,dx}{[(x^2-b^2+h^2)^2+4b^2h^2)]^{\frac{1}{2}}}$$

$$= \pi\rho\log_e\frac{a^2-b^2+h^2+\sqrt{(a^2-b^2+h^2)^2+4b^2h^2}}{2h^2} \qquad (4)$$

For points on the central axis, where $b = O$, this reduces to

$$I_p = \pi\rho\log_e\left(1+\frac{a^2}{h^2}\right) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

It may be shown [6] that the dose contours of such a disc source are ellipses with their foci at the ends of the diameter of the disc. Fig. 31 shows the dose contours calculated for a disc source of radius 3·0 cm. and $\rho = 1$ mgm./cm.^{2}

(iv) APPROXIMATE CALCULATION FOR COMPLEX RADIUM SOURCES [7]

Approximate calculations of the dosage distribution around complex radium sources may sometimes be made by treating the sources as approximately point sources or as a number of point sources approximately placed according to the real shape of the source. It is then only necessary to know the intensity $\left(\frac{m}{r^2}\right)$

due to such point sources at various distances. For this purpose Mayneord [7] has drawn up tables giving the dosage-rates at various distances from point sources of various radium contents of known filtration (0·5 mm. Pt.). An abbreviated version of the tables is given in Appendix III.

Various other methods of gamma ray dosimetry have been attempted upon the basis of one or other of the effects brought about by the absorption of gamma ray energy in various materials. Use has thus been made, at one time or another, of the biological effect, chemical effect, photo-electric effect, photographic effect, heating effect and power of ionizing air. Methods of dosage based upon various biological effects of gamma rays have received considerable attention, and many Americans, following the school of Failla and Quimby at the Memorial Hospital, New York, make considerable use of the " Skin Erythema Dose " as a measure of total dosage. The use of the chemical or photoelectric effects of gamma rays as a means of dosage measurement has not led to any significant advance. Under certain circumstances the photographic action of gamma radiation may be employed to measure dose in a satisfactory manner. An ideal method of dosage would be in terms of absolute energy absorption per c.c. of medium (tissues) measured in calories or some other energy unit. This has been attempted, but the difficulties of measuring such small amounts of energy lead to a very low degree of accuracy, and, at the present time, the best approach to the measurement of this quantity seems to be the indirect one which makes use of the ionization produced

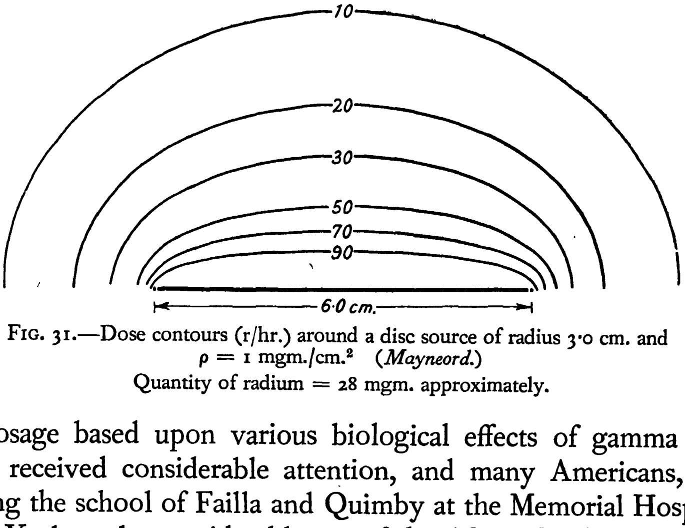

FIG. 31.—Dose contours (r/hr.) around a disc source of radius 3·0 cm. and $\rho = 1$ mgm./cm.^{2} (*Mayneord.*)
Quantity of radium = 28 mgm. approximately.

in air by the radiation. It is by means of this last method that most modern measurements of dosage are made.

3. Biological Methods of Dosage

In this method " dose " is measured as that quantity of radiation which produces some specific biological effect and various biological reactions have been considered for this purpose. Thus it was suggested by Russ as early as 1918 [8] that one might use as a standard dose, the amount of radiation necessary to kill mouse cancer, the amount to be determined experimentally and called the " rad." Other workers have since made use of killing effects on small biological organisms, such as Ascaris or Drosophila eggs. The biological method cannot be used directly for the measurement of radiation dose because there is no simple proportionality between biological effect and dose, but it can be used to establish a standard, if the biological material lends itself to sufficiently accurate experimentation. Thus the necessary calibration curves can be developed only if sufficient individuals are used, and for this reason the experimental method is readily applicable to such a reaction as Drosophila killing as has been shown by Exner and Packard [9] and others.

At the Memorial Hospital, New York, Failla and Quimby and their co-workers have done a considerable amount of work over a period of years [10] in which some form of skin erythema has been used as the standard biological reaction. On the basis of this work it became possible for radiologists anywhere to compare doses delivered by various methods of radium therapy and to express these in terms of erythema doses. Further details of the way in which such methods were developed will be given in later chapters.

4. The Photographic Method of Dosimetry

This method depends upon the blackening of a photographic film produced by the action of the gamma rays, and it has been shown that this is analogous to that produced by X-rays.[11] The fact that the blackening of a photographic film by X-rays depends only on the exposure (*i.e.*, the *quantity* of radiation) and is independent of the *intensity* of the radiation has been established over an intensity range of 10,000 to 1. Rogers [12] has proved that this law holds in the case of gamma rays over an intensity range of about 10 to 1, and Bell[11] has confirmed it over an intensity range of about 100 to 1. Thus the photographic blackening B is related to the intensity of radiation I_r and the time t of its action by the equation :—

$$B = I_r \times t \text{ (Bunsen-Roscoe Reciprocity Law)} \quad . \quad (6)$$

Table 7 shows the results that were obtained by Bell in confirmation of this law. The intensities are expressed in terms of the modern ionization unit, the röntgen (r), which is discussed later in this chapter, and it is seen that within the limits of experimental error, the product $I_r \times t$ has a constant value regardless of the actual intensity I_r. (Strictly, of course, I_r is dose-rate and not intensity.)

The photographic blackening produced is measured by some form of microphotometer (*e.g.*, the Moll microphotometer). Density of blackening B is expressed as $\log_{10}$ of the "opacity." Thus, if a light of intensity I_0 is incident upon the silver deposited as a result of the action of the gamma rays, and an intensity I is transmitted, the density is given by :—

$$B = \log_{10}\left(\frac{I_o}{I}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

TABLE 7.—*Relation between the Exposure ($I_r \times t$) and Intensity (I_r) of Gamma Rays (Bell)*

DOSAGE—RATE OF INTENSITY I_r in r/min.	EXPOSURE TIME IN MINUTES for B = 0·5	EXPOSURE $I_r \times t$ for B = 0·5
0·00227	208	0·471 r
0·00293	158	0·463 r
0·00345	137	0·472 r
0·00464	103	0·476 r
0·00608	78·3	0·476 r
0·00874	50·8	0·445 r
0·0133	35·2	0·468 r
0·0235	20·4	0·479 r
0·0538	8·60	0·463 r
0·214	2·15	0·460 r
	Mean :—	0·465 r

The proportionality between the blackening B and the exposure ($I_r \times t$) does not hold for all values of B. Rogers[12] found that it held for blackenings up to 0·8 (agfa duplitised film), and Bell[11] showed that it held up to about unit blackening for two different kinds of X-ray film; although the shape and slope of the curves relating blackening and exposure were somewhat different for the two films (see Fig. 32). The makes of film were not stated. It may be seen from Fig. 32 that a lead backing to the film acts as an intensifying screen, but when the method is used for purposes of recording gamma ray dosage, such intensification should on no account be used. Indeed, the film holding cassette should be constructed of light materials of a suitable thickness (for measurements in air), so that all those conditions are fulfilled which we shall see to be necessary for the measurement of gamma radiation by means of small ionization chambers. The presence of a heavy metal (silver) in the photographic emulsion prevents the film itself from fully complying with these conditions, and this is a distinct disadvantage of the method.

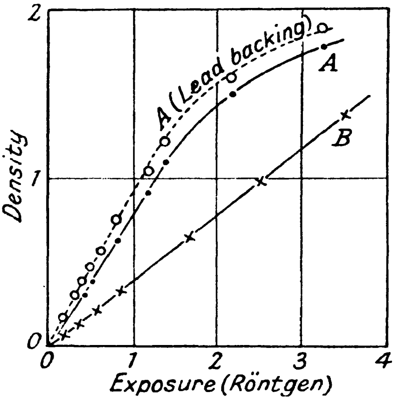

FIG. 32.—Density exposure curves of photographic emulsions for radium gamma rays. A and B: different makes of double-coated films. Dotted curve: film of type A backed by 0·1 mm. of lead. (*Bell.*)

In practice, as a routine method of radium dosimetry, the photographic method is little used, except perhaps for protection measurements where it is desired to record the small, stray doses of radiation received by personnel over a period of one or more days. In this connection, it may be mentioned that the National Physical Laboratory has established a service at the request of the Ministry of Health for testing the amount of stray radiation received by X-ray and radium workers. The test is made by means of photographic films, which, after exposure to the working conditions, are developed under rigid control. Details are given in a Ministry of Health Circular 2718, dated November 16th, 1942.

The method, however, does seem to offer advantages of convenience and simplicity, for pieces of film can be placed conveniently within " phantoms " so as to investigate dosage within the body. In any single experiment pieces of the same film should be used and these should all be developed together so that all the factors are constant. Thus a number of workers have made use of the photographic method at various times. Its use as a method of radium dosimetry has been considered by Holthusen and Hamann.[13] Friedrich, Rosenberger and Goldhaber[14] made measurements which they compared with those made by the ionization method and Kirchoff and Beato[15] examined the relative distribution of radiation around various radium sources.

5. **The Calorimetric Method** (Dosage in ergs per c.c.)

Upon theoretical grounds the ideal method of dosimetry would appear to be that in which one measures the actual energy absorbed in a volume element (as indicated by rise in temperature) of tissues when they are irradiated. For the measurement it would, of course, be necessary to resort to a " phantom " composed of tissue-like materials. In principle it is possible to measure directly, by calorimetric methods, the rate at which energy is being absorbed from gamma radiation at any point in such a phantom. Stahel[16] in fact, has explored the possibility of such a method. A radium source was mounted at the centre of a large, spherical, glass calorimeter filled with petrol ether and the total energy absorbed from the gamma rays emitted by the source, was measured by means of the expansion of the petrol ether. The energy of the α- and β-rays and soft gamma rays from the source was absorbed and removed by a water flow device and the calorimeter was calibrated by means of known quantities of heat generated by a small heating coil. In order to express the results in terms of the energy absorbed at a point, the relative distribution of intensity was explored throughout the medium by means of a small, liquid-filled ionization chamber, the liquid filling being petrol ether. By graphical integration over the whole volume of the calorimeter, the relative units used were related to the total energy absorbed, and so the energy absorbed per c.c. of water, at any distance from the radium source was determined: allowance was made for the difference in the densities of petrol ether and water.

Chiefly because of the extreme difficulty of the microcalorimetric technique, the method has not commended itself to any general use. An attempt to repeat Stahel's experiments and to develop the method was made by Fewkes,[17] but it met with little success. This was mainly because, in spite of much more elaborate lagging precautions than those used by Stahel, extraneous heat was always much greater than that generated by the absorption of gamma radiation. However, the liquid-filled ionization chamber, in view of its liquid filling and its very small dimensions, represents quite an experimental adventure, for it does measure directly, the ionization within the absorbing medium itself.

The low order of accuracy of this method has been confirmed more recently by Stahel[18] himself in a comparison of this measurement with the modern air ionization unit, the röntgen (*r*). This comparison indicated that 1 röntgen was equivalent to 222 ergs/c.c. of water. On the other hand, calculation of this relation, (*a*) by means of the energy absorbed in the formation of an ion pair, and (*b*) from the known energy spectrum of radium (B + C), gave values of 93 and 103 ergs/c.c. of water respectively. The agreement between the latter values is good considering the various assumptions and approximations required for the calculations so that the experimental result must be in serious error. Stahel considers this to be due to extra heat generated in the petrol ether, possibly by chemical decomposition.

6. Dosimetry by Means of Ionization in Air

The method of dosimetry which has proved the most practical and fruitful is that based upon the ionization produced in air by the radiation. This ionization is produced by the recoil- and photo-electrons generated in the absorption of the radiation and therefore is a measure of the energy of these particles, that is, of the energy absorbed. In addition, we have already seen (Chap. II) that this energy absorption (or ionization) in air very closely parallels that in a " tissue-like " substance such as water. The ionization in air, therefore, would seem to provide a most convenient basis for a method of radiation dosimetry. Accepting these ideas as a beginning, much research has been done to discover under what conditions the ionization in air may be taken as a measure of the dose in living tissues.

An advantage of the ionization method that seemed to most to be of the utmost value, was that it offered an opportunity of measuring gamma ray doses in terms of the same unit, the international röntgen (*r*-unit), which has proved so satisfactory for the measurement of X-ray dose. If this could be done, a basis was available for the comparison of the relative biological effectiveness of X-rays and gamma rays.

The study of the possibilities of this method of measuring gamma ray dosage has been approached from two different aspects : (*a*) *via* the ionization measured in " free-air " and (*b*) *via* the ionization in an " air-wall " chamber. Many problems have arisen as a result of this study.

7. Gamma-ray Ionization in " Free-air "

The " röntgen "—its Realisation for X-rays. The unit of X-ray quantity, called the " röntgen " (denoted by *r*), was defined at the Second International Congress of Radiology in 1928 * as "the quantity of X-radiation which, when the secondary electrons are fully utilised, and the wall effect of the chamber is avoided, produces in 1 c.c. of atmospheric air at 0° C. and 760 mm. mercury pressure, such a degree of conductivity that one electrostatic unit of charge is measured at saturation current."

In attempting to realise this unit unambiguously, resort was made by many workers to the " free-air " ionization chamber in which the X-ray beam entering the chamber is limited by a system of diaphragms and so prevented from striking the chamber walls. Any possibility of wall effect being included in the measurement is thus eliminated. The essentials of the chamber design, etc., for this type of measurement are illustrated in Fig. 33. Further details may be found by reference to some of the many accounts of such measurements that have been published.[19, 20, 21].

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* The initiative on the necessity for an X-ray unit had been taken by a joint meeting of the British Röntgen and Physical Societies in 1923 and at the First International Congress of Radiology, held in London in 1925, it was decided that an International Committee be appointed to consider the establishment of an X-ray standard of intensity and an X-ray unit. The definition decided upon in 1928 was greatly influenced by the work of Villard, Beknhen, Dauvillier, Seitz and Wintz, Kroenig and Friedrich, Solomon and many others. An appreciation of the steps by which the definition was reached may be gained from the report of the Physics Section of the 1925 Congress published in the *British Journal of Radiology* (Röntgen Society), Vol. XXIII, April, 1927. It is of great interest to note that in the discussions that took place, Mallet and Coliez of Paris both pointed out the necessity of unification of dosage so that the X-ray unit would also be available for measurements of gamma rays.

The complete apparatus is quite elaborate and very special attention has to be given to the definition of the X-ray beam, to the determination of the volume of air actually ionized, to the saturation potential of the chamber and to the spacing of the electrodes, which must be sufficient to ensure complete utilisation of the secondary electrons produced by the passage of the X-ray beam. In addition, the absence of field distortion between the high potential electrode and the collector must be ensured.[19, 20, 21] Then, if a charge Q electrostatic units (e.s.u.) is collected in a time t seconds and the ionized volume of air is v c.c., the dosage-rate which this corresponds to is:—

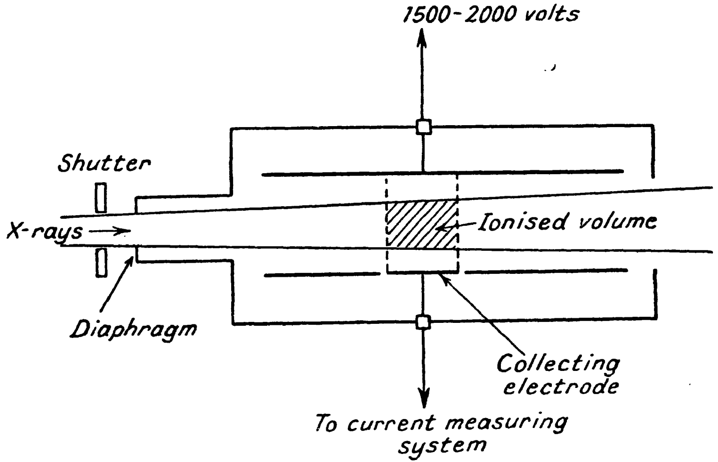

FIG. 33.—Illustrating principle of "Free-air" ionization chamber.

$$\frac{Q}{f \times v \times t} \text{ e.s.u./c.c./sec. (röntgens per sec.)} \quad . \quad . \quad . \quad (8)$$

f being the factor which reduces the atmospheric pressure and temperature prevailing at the time, to those stated in the definition.

For X-rays generated at kilovoltages in the neighbourhood of that most commonly used in X-ray therapy (about 200 kv.), this method of approach to the realisation of the röntgen has proved entirely satisfactory and an intercomparison that was made between the national laboratories of America, Germany and Great Britain resulted in an agreement that was within $\frac{1}{2}$ per cent.[22]

The "Free Air" Measurement of Gamma Rays in röntgens. The above method has been used by a number of workers in attempts to measure gamma radiation in terms of the same unit. We have seen already that a quantity frequently occurring in the subject of gamma ray dosage is the intensity, or more precisely, the dosage-rate, at a distance of 1 cm. from a 1 mgm. point source of radium filtered by 0·5 mm. platinum. Thus it is this quantity that many physicists have endeavoured to express in terms of the röntgen. Results obtained by various workers with free-air chambers showed extremely wide differences between themselves (see Table 8), and it became apparent, that as it stood, the method was not suitable for the measurement of gamma rays. Moreover, these results conflicted with those obtained by means of "air-wall" chambers, by which method, fairly consistent results were obtained under such suitable conditions as we shall discuss later.

TABLE 8.—*Gamma Ray Dosage-rates measured with Free-air Chambers*

Author	Dosage-rate at 1 cm. from 1 mgm. of radium filtered by 0·5 mm. Pt. *i.e.* 1 Imc. (cm. mgm.-el. hr.)
	r/hr.
Bruzau[23]	6·7
Failla and Henshaw[24]	1·96
Mayneord and Roberts[25]	3·06

It was suggested[25] that the discrepancies were due to the dimensions of the parallel-plate, free-air chambers that had been used, which were inadequate when the radiation has the extremely short wave-lengths of gamma rays. It had been found that in order to fulfil the conditions required by the definition of the röntgen when X-rays of ordinary therapeutic qualities were involved, it was sufficient to have plate dimensions and plate separations of the order of 20 cm., and it had seemed as if these dimensions were satisfactory for gamma rays also. By a consideration of the sources of the ionization measured in a parallel-plate measurement of gamma rays, Mayneord and Roberts[25] concluded that the chamber would measure the real energy absorption in the air volume concerned, only if the length of air inside the chamber and between the chamber and radium source, was equal to the range in air of the fastest secondary electrons generated, since electrons generated in this column of air, must be allowed to contribute their quota of ionization to that measured. We have already seen (Chap. II) that the fastest recoil electrons have a forward range in air of some 3 or 4 metres, so that this condition is difficult to fulfil in practice. Furthermore, it seemed necessary that plate and plate separation dimensions should also be very large and of the order of 1–2 metres or even more.

In spite of the obvious experimental difficulties involved, attempts have been made to realise these extreme conditions. Kaye and Binks[26] at the National Physical Laboratory, used a chamber some 3½ metres high, the plate separation of which could be varied between 25 cm. and 3 metres and the radium source was placed several metres from the chamber. Their final results indicated that the Sievert unit dose-rate (Imc.), as measured with such a chamber, is of the order of 7–8 röntgens per hour, a result that agreed reasonably well with the values obtained with suitable "air-wall" chambers (see later). Friedrich[27] later conducted similar experiments, using a chamber half-way between floor and ceiling in a hall 100 × 50 × 22 metres, when he found that equilibrium was established at a distance of 20 metres from the radium source which provided the collimated beam of gamma rays. On the basis of these measurements he found a value of 7·8 röntgens per mgm.-hour at 1 cm. distance from a point source of radium filtered with 0·5 mm. platinum.

Taylor and Singer[28] have further confirmed these ideas by measurements they have made quite recently with a plate separation of only 30 cm., but they worked with air at 10 atmospheres pressure. If the matter of attaining equilibrium conditions depends only on the number of electrons in the material traversed, such conditions are equivalent to a chamber ten times as large with the air at atmospheric pressure. Under these conditions saturation current was still not perfectly attained even with a plate voltage of 20 kv., but the true value of the current was deduced from the theories of columnar ionization. Taylor and Singer consider that the greatest inaccuracy lies in the self-screening of the radium source and the value they obtained for the Sievert unit was 8·16 ± 0·04 r/hr. This measurement may, without doubt, be considered one of the best that has been made.

The experimental difficulties of this method of measuring gamma rays in röntgens make it rather unsuitable for a standard method. This is one of the main reasons why more attention has been paid to the method which makes use of the "air-wall" ionization chamber.

8. Gamma Ray Ionization in "Air-Wall" Chambers

An alternative to the "free-air" method of measuring the ionization due to gamma rays is to use a small, enclosed chamber, so that the rays pass through the walls. In such a chamber the ionization is due in the greater part to the secondary electrons emitted from the walls. The ionization generated directly in the air itself forms only a small part of the total. From the point of view of practical therapy this type of chamber has much to recommend it, since by suitable design, it may be made independent of the direction from which the radiation is received, and may therefore be used in the kind of circumstances that most frequently arise, as for instance, in the measurement of doses at a depth in tissues. Such a chamber is said to be "air-walled" if the atomic number, or effective atomic number of its walls, is equal to the effective atomic number of the air within it, when the ionization current inside the chamber should be equal to that in the same volume of free-air. This idea was developed for therapy largely by Fricke and Glasser[29] who defined an "air-wall" chamber as: "A chamber with walls of the same effective atomic number as air (7·3) which gives an ionization current proportional to the volume and equal to the ionization in the same volume of air within an infinite extent of irradiated air." The work of Fricke and Glasser was largely concerned with the measurement of X-rays, so that in order to ensure that the electronic emission from the chamber walls (recoil electrons and photo-electrons) was similar to that from air, the equivalence of atomic numbers was essential. In the case of gamma rays the problem seems more simple, for we have seen that with such short wave-lengths, the electronic emission consists almost entirely of recoil electrons and, moreover, this emission is practically independent of atomic number for all light materials with atomic numbers round about that of air (6–13).

The fundamental theory applicable to air-wall chambers was first given by Bragg[30] but it has been re-emphasised recently in connection with the measurement of the ionization produced by gamma radiation and its relation to the absolute measurement of gamma ray energy[31, 32, 33, 34]. The theory indicates that we may measure gamma ray dose by this method with sufficient accuracy for clinical work provided certain conditions, which we shall examine further, are fulfilled. This is supported by experimental evidence based upon the application of the method to the absolute measurement of the gamma ray energy emitted from a known quantity of radium.

Gray has considered the ionization produced in a small, air-filled cavity within an extensive irradiated medium. In such a cavity the secondary electrons arising in the medium far outnumber those arising in the air itself so that it is the former which are mainly responsible for the ionization. The number, speed and direction of the secondary electrons crossing each point of the cavity boundary are exactly the same as they are at the same point in the homogeneous medium.[31] Then provided that only a small fraction of the energy of the secondary electrons is used up to produce ionization in crossing the air cavity, the ionization produced in the cavity bears a simple relation to the gamma ray energy that would be absorbed at the same point in the medium. This is :—[32]

$$E_v = J_v W . \rho \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where E_v is the gamma ray energy absorbed per unit volume of the medium, J_v is the ionization per unit volume produced in air (*i.e.*, the number of ions formed) and ρ is the ratio of the rates at which energy is lost by the individual electrons in the medium and in air (*i.e.*, the ratio of the stopping powers of the medium and the gas for the secondary electrons). W is the average energy lost by the secondary electrons per pair of ions formed in the air. This has been shown to be constant for all secondary particles having energies between 1 and 1,000 kv. and to have a most probable value of 33 electron-volts or 53×10^{-11} ergs.[32, 34]

The relation (9) is most exact when the medium and the air within the cavity have the same atomic number. This is when the cavity has a perfect "air-wall" and with this condition ρ is equal to the ratio of the specific gravities of the medium and the air.

If the gamma radiation producing the secondary particles has an energy flux E, then $E_v = E\ (\sigma_a + \tau)$, since we have seen that $\sigma_a + \tau$ represents the fraction of the energy reappearing as secondary electrons, where σ_a and τ are the respective absorption coefficients of the medium. Thus we may write (9) as :—

$$J_v = \frac{E\,(\sigma_a + \tau)}{W.\rho}$$

or, since τ is negligible for gamma rays when the medium is a light element,

$$J_v = \frac{E\sigma_a}{W.\rho} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Equation (10) shows that the ionization is dependent, not only upon σ_a, but also upon ρ. Murdoch and Stahel[35] and Friedrich and Schulze[36] have published results which suggest that ρ is constant for all light elements, but since they find the constancy to include materials even of so high an atomic number as copper, the findings have an element of doubt. Gray[32] found ρ to vary smoothly with atomic number, increasing by about 9 per cent. between $Z = 6$ and $Z = 13$, and a further 8 per cent. between $Z = 13$ and $Z = 29$. These values are shown graphically in Fig. 34, the curve having been adjusted to pass through unity at $Z = 7{\cdot}3$ (Z_{eff} for air), so that the ordinates express the extent to

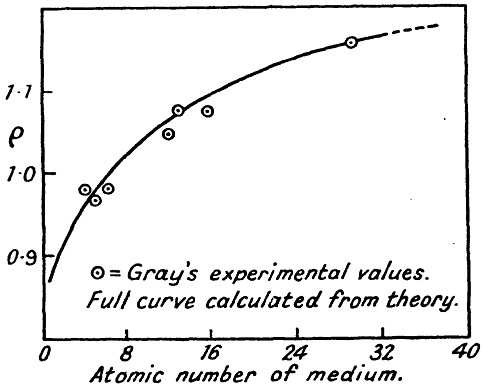

FIG. 34. (Gray).

which the value of ρ differs from the simple ratio of the electron densities for a medium of atomic number Z. The full line was calculated by Gray from the recent theories of the stopping of electrons by matter, and it may be seen how good is the agreement with the experimental determinations. Differences in the value of ρ of the same order and character, but over a smaller range of atomic numbers, have also been observed by Mayneord and Roberts,[37] Wilson [38] and others. However, if light atom materials with atomic numbers between, say, 6 and 13, are considered, the variations of ρ are only a few per cent. and correction may be made quite easily.

The above theory has been subjected to various experimental tests. Equation (9) indicates that the ionization should be inversely proportional to ρ, but since ρ itself will obviously be inversely proportional to gas pressure, it follows that the ionization should be directly proportional to gas pressure. This was tested by Gray [32] and found to hold with air volumes of 2 c.c. and 0·1 c.c. within graphite ionization chambers, for pressures between 74 and 10 cm. of mercury. Also, the ionization per unit volume of the gas should be independent of the chamber volume. Using chambers ranging in volume from about 1 c.c. down to 0·005 c.c., Gray [32] showed that this was so within experimental error. Many other workers have considered these questions and their results have been adequately summarised quite recently by Sievert.[39] These results are extremely conflicting, and if any change in ionization per unit volume with change in volume or in pressure does occur, the change would seem to be very small. Sievert himself suggests that such changes do occur. He presents some evidence to support his contention,[39] and it appears that the subject is worthy of still further study.

The validity of Gray's theory is stressed by the results he obtained in a comparison made between the ionization and calorimetric methods of measuring the absolute rate of emission of gamma ray energy by radium (B + C). The ionization was determined [33] by means of small aluminium ionization chambers at distances between 2 and 50 cm. from a radon source situated at the centre of a large block of aluminium. Using the facts already discussed, the results were used to determine the rate of emission of gamma ray energy. The value found was 8·7 ± 0·2 calories per gram, per hour. This may be compared with the results obtained by Zlotowski,[40] who carried out an extremely refined calorimetric measurement of the same quantity and found a value 8·9 ± 0·2 cals per gram, per hour. The close agreement suggests that any errors that may exist in the theory of cavity ionization by gamma rays must be very small.

Summing up, it has been seen that we may measure the ionization produced in air by gamma radiation by means of a walled chamber, provided the effective atomic number of the wall material is close to that of air. Any slight difference in atomic number may be allowed for quite easily. If required, this ionization may be related to the energy absorbed within a light atom medium comparable to tissue.

For the practical determination of the Sievert unit dose by this method, the measurement is made, not in an extensive medium, but with a chamber having walls of a finite thickness. In this and other connections, we may usefully consider the construction of such ionization chambers in respect of (i) Wall Material, (ii) Wall Thickness. The question of the dimensions of the air volume also arises, but this will be dealt with in Chapter IV when the design of actual instruments for measurements are discussed.

9. "Air-wall" Materials

A wide variety of homogeneous and composite materials have been used in the many investigations that have been made of the ionization in "air-wall" chambers due to gamma rays. Details of some of these materials are listed in Table 9.

Of the homogeneous materials graphite has been the most widely used, chiefly because its atomic number is so close to that of air. It may be obtained in an extremely pure state (as rods, etc.) and machines extremely well. "Elektron" metal is an alloy containing nearly 93 per cent. of magnesium which has been widely used, especially in a special measuring technique developed by Sievert[4] which is described in the next chapter. This alloy has an effective atomic number of 13, but machines very much better than aluminium. For the special technique mentioned it has the advantage over graphite that it cannot produce dust (as does graphite) which is ruinous of really high insulation. It has the disadvantage that it tarnishes very readily.

As a result of research into the production of an "air-wall" material suitable for measurements over a wide range of X-ray

TABLE 9.—*Some " Air-wall " Chamber Materials*

Material	Authors
Graphite Z = 6	Mayneord and Roberts[25, 37] Gray[32, 34] and others.
" Elektron " metal 92·9% Mg 3·4% Al 3·3% Zn $Z_{eff} = 13$ 0·2% Cu	Sievert[4] and others
Aluminium Z = 13	Murdoch and Stahel[35] Gray[33]
" Aerion " bakelite and graphite composition.	Zimmer[41]
A mixture :—(97% C + 3% Si) + 35% celluloid	Miehlnickel and Osterwisch[42]
Graphited celluloid	Sievert
Composite mixture of bakelite and graphite + a small percentage of titanium or vanadium oxide.	Grimmett and others[43]

wave-lengths, Zimmer[41] produced a bakelite-graphite composition which appeared to fulfil this purpose. Thus for gamma ray measurements it is especially good. This material has been named " Aerion " and has been used by a number of workers. Specially hard tools are needed to machine this material satisfactorily, and it is more usual to use a pressing and moulding method similar to the processing of thermo-setting plastics. Workers at the Radium Beam Therapy Research,* London,[43] report that they find the original Aerion not to have the properties of wave-length-independence that Zimmer claims for it, and they have improved the product in this respect by the addition of a small percentage of titanium or vanadium oxide. This new material is conveniently moulded under pressure and gives chambers with excellent electrical and mechanical properties.

Celluloid coated with graphite (pencilled) to render it conducting and many other plastic materials similarly treated are sometimes used for the construction of chambers. Other authors have used various coatings (*e.g.*, $Al_2 O_3 + C$) on the inside of chambers in an endeavour to produce an electron emission similar to that from air. Reasons have been given, however,[34] why a homogeneous material is to be preferred.

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* The Radium Beam Therapy Research is now known as the M.R.C. Radiotherapeutic Research Unit, and it is housed at Hammersmith Hospital, London, W.12.

10. Wall Thickness of Ionization Chambers

When considering the "free-air" measurement of gamma radiation it was seen to be a necessary condition that the air volume, within which the measurement is made, must be surrounded by a volume of air of dimensions equal to the range of the secondary electrons generated in the air by the radiation. In the case of the "air-wall" chamber, the surrounding air is replaced by a material of similar atomic number but greater density, and the range in the material, of the secondary electrons generated in it by the radiation, determines the wall thickness necessary to bring about electronic equilibrium. If a suitable thickness is used the conditions of the theoretical air cavity are reproduced.

When measurements are made with thin-walled chambers, in which the walls are considerably thinner than the equilibrium thickness, it has been seen in many experiments,[25, 34, 38, 44, 45] that almost any result may be obtained depending upon the actual conditions used. In addition to the secondary electrons from the walls of the chamber itself, such chambers also record ionization due to secondary electrons entering the chamber from the surrounding air and from neighbouring materials such as filters, etc., and the amount and nature of this ionization depends upon the experimental conditions. These factors have been studied by examining how the ionization within a chamber depends upon the thickness of the wall, upon what portion of the wall is thickened and also upon whether or not the gamma ray beam is canalised.[25, 26, 34, 37, 38, 44, 45] All these experiments agree in showing that an equilibrium value of ionization is reached, when the wall thickness of the chamber is of the order of the range in the wall material, of the electrons generated in it by the radiation. For a material such as graphite this thickness is of the order of 4 mm. When the wall thickness is increased much beyond this value, absorption of the gamma radiation becomes apparent and the ionization value falls almost linearly, at least up to a wall thickness of 20 mm.

This is clearly seen in Fig. 35 which represents some results obtained by Mayneord and Roberts[37] for ionization chambers with graphite walls. The equilibrium wall thickness ensures at the same time

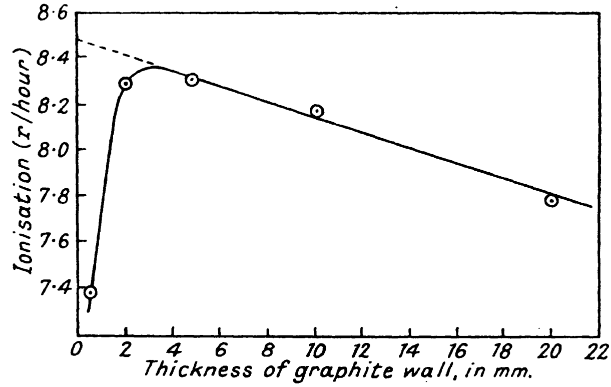

FIG. 35.—Variation of the ionization within an " air-wall " chamber with increase in wall thickness. (*Mayneord and Roberts.*)

that secondary corpuscular radiation from surrounding objects does not enter the chamber and so confuse the gamma ray measurement.[38, 45]

In view of the fact that the range of the fastest secondary electrons

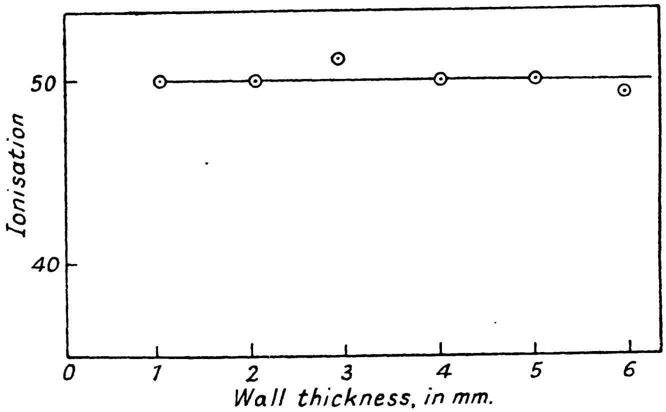

FIG. 36.—Dependence of the ionization measured in a water phantom upon the wall thickness of the chamber. (*Friedrich and Zimmer.*)

generated by the hardest radium gamma radiation is of the order of 6–7 mm. it is surprising that a 4 mm. thick wall suffices for equilibrium. It has been shown, however, that when all the pertinent data are considered this lower value is to be expected. Thus some two-thirds of the ionization is produced by electrons generated within 0·2 mm. of the inner surface of a graphite chamber, and all but 10 per cent. if the ionization is due to secondary electrons generated at depths less than 0·7 mm.[34] The latter fact is seen clearly from Fig. 35.

For measurements made within a light atom medium such as a water phantom, we might expect that the wall thickness of the chamber would be immaterial. That this is so has been shown by Friedrich and Zimmer,[45] whose results are shown in Fig. 36. We see, therefore, that in practice it appears to be easier to make a satisfactory measurement of gamma radiation within a suitable tissue-like medium, than it is to make such a measurement in air.

It has been suggested that in making measurements in air, the effect of thick walls is to give rise to excess ionization due to scattered gamma rays. It has been shown, however,[34, 37] that a reduction in ionization occurs of an amount equal to $\sigma_a d$ where d is the thickness of the wall, so that a correction for absorption may be made. This absorption, in fact, explains the fall in ionization with increase in wall thickness seen in Fig. 35, and Mayneord and Roberts[37] used the slope of such curves to deduce values of σ_a for graphite, magnesium and paraffin wax which agree very well with those calculated by means of the Klein-Nishina formula. In order to apply the necessary correction for absorption, these same authors have extrapolated curves such as that of Fig. 35 back to zero wall thickness. Gray[34] has preferred simply to apply the theoretical correction, which, for a 3 mm. graphite wall, considered by him as sufficiently thick, amounts to about 2 per cent.

As a result of investigations such as have been outlined above, it is considered by the majority of physicists concerned with the work, that it is now possible to measure the gamma rays of radium with small "air-wall" chambers under conditions which justify the expression of the measurement in röntgens, at least to a degree of accuracy that is sufficient for clinical practice. However, since these conditions do not implicitly accord with the original definition of the röntgen, it was redefined at the Radiological Congress held in 1937 at Chicago. This definition was as follows: "The röntgen shall be that quantity of X- or gamma radiation such that the associated corpuscular emission per 0·001293 gm. of air, produces in air, ions carrying 1 e.s.u. (quantity) of electricity of either sign."

The mass of air referred to in this definition is that of 1 c.c. of dry air at N.T.P. Attention had already been drawn to the effect of humidity upon the ionization measurement and to the advantages of working in terms of a mass of air in a paper by Quinton.[46] This definition still leaves the possibility of measuring dosage in röntgens by means of a " free-air " chamber, but we are also able to measure the same quantity by means of a small, walled ionization chamber. It seems to imply measurement of the energy converted into air ionization, it is not necessarily a measurement of the energy absorption in tissues.

11. " Air-wall " Chamber Measurements of Radium Gamma Rays in röntgens

From time to time a number of workers have used the air-walled ionization chamber to determine the dosage-rate (in röntgens) at a distance of 1 cm. from a 1 mgm. point source of radium element totally enclosed in 0·5 mm. platinum filter. Before examining the results that have been obtained it will be useful to consider some practical points which have a bearing upon the accuracy of the results.

A possible disturbing influence in the measurement is gamma radiation scattered from objects round about or from the walls of the room in which the experiment is conducted. That this factor may assume considerable proportions if the distance between the chamber and the radium source is large, was found by Kaye and Binks[26]; they showed that as the distance increased from about 1 metre up to 9 metres, the ionization increased by more than 25 per cent. It may be shown, however, that for distances of the order of 10 to 20 cm., any errors are negligible if the measurement is made at the centre of an average sized room.

In order to correlate the ionization measurement with the radium quantity and distance, a calculation must be made in accordance with the principles discussed earlier in the chapter. This necessitates assuming the validity of the inverse square law, and we are concerned to know whether the " distance " is to be measured to the geometrical centre of the chamber or to some other point. In this connection Gray[34] has shown that if measurements are made with a chamber having a spherical air volume of 1 cm. diameter at 10 cm. from the source, and the distance is measured to the geometrical centre of the chamber, the error incurred will certainly not exceed 1 per cent. Mayneord and Roberts[37] reached the same conclusions. Gray[34] has also shown that even at distances as small as 9 mm. (only a little greater than the range of secondary electrons) from a radium source, the intensity calculated on the assumption of the inverse square law will certainly not be in error by more than 4 per cent.

The most recent determinations of the Sievert dose in röntgens are those of Gray,[34] Mayneord and Roberts[37] and White, Marinelli and Failla,[47] who have paid the most strict attention to all the factors affecting the measurement. Their results are collected together in Table 10, which also gives the values obtained for filtrations other than 0·5 mm. platinum.

TABLE 10.—*Values of the Sievert Dose in röntgens*

Authors	Filtration	1 Imc.-hour (cm. mgm.-el.-hr.)
Gray[34]	0·5 mm. Pt.	8·4 r
Mayneord and Roberts[37]	0·5 mm. Pt.	8·3 r
	2·5 ,, ,,	6·3 r
	5·0 ,, ,,	4·6 r
White, Marinelli and Failla[47]	0·5 mm. Pt.	8·56 r

Many other values of this quantity have been published which have been summarised by Zimmer,[48] and these range between 7·6 *r* and 9·2 *r*. Some of these values, however, are subject to corrections, which were omitted, and when these are made, most of the values fall within the range of 8·0 *r* to 8·5 *r*, so that within 1 or 2 per cent. the Sievert unit dose seems to have been measured in röntgens quite definitely.

The method used by White, Marinelli and Failla[47] to determine their value given in Table 10 is so unusual as to merit special mention. The chambers they used were essentially very thin shells of air completely surrounding the radium source, which was first embedded in sufficient air-wall material to produce electronic equilibrium. Around this radium container a series of hollow spheres of different sizes could be mounted, giving air shells of varying thicknesses. The outer surface of the radium container and the inner surface of the surrounding shell formed the electrodes of the ionization chamber, and the ionization in the intervening space was measured. Thus it was possible to extrapolate the results to find the ionization in an infinitesimally thin air shell; this eliminated any error due to size, shape or orientation of air volume.

12. Derivation of the Sievert Dose (cm. mgm.-el.-hr.) from Eve's Constant

If a point source of gamma radiation is imagined situated in an infinite volume of air, then the number of ion pairs produced per second at a point r cm. from the source may be designated J and may be written as:—

$$J = K\frac{M}{r^2}.e^{-\mu r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Where M is the quantity of radium contained in the source, μ is the absorption coefficient of the radiation in air and K is the number of ion pairs produced per c.c. of air at a distance of 1 cm. from the quantity of RaC in equilibrium with 1 gram of radium. K is known as Eve's number[49] and refers usually to RaC alone, but may include RaB also. When this inclusion is made it is seen that the constant is a measure of the ions/c.c./gm./sec. which bears an obvious relation to the quantity e.s.u./c.c./mgm.-hour which we have already discussed in some detail. In view of this relationship various authors have calculated the value of the Sievert unit dose from Eve's number, recognising that the accuracy obtained was dependent upon the accuracy of the experimental values of the constant. Thus Mayneord[50] derived a value of 8·7 *r* based upon the experimental value of Eve's constant determined by Reitz,[51] who used very thin-walled ionization chambers and extrapolated to zero wall thickness. Gray[34] showed that objections may be raised to this determination of Eve's number, and that if suitable allowance is made for this fact, the value obtained is very close to 8·4 *r*, in very good agreement with the above experimental values.

13. Relation of other Dosage Units to the röntgen

Before the establishment of the röntgen as the dosage unit most suitable for radiation therapy, a number of other units had been in use in different countries and institutions. Therefore, in order to be able to correlate data collected by means of these units, with similar data obtained at the present time, it is useful to have some idea of the relationship between these older units and the röntgen.

(*a*) THE SOLOMON R UNIT. The Solomon R unit was defined as the intensity of X-rays producing the same ionization as 1 gram of radium element filtered by 0·5 mm. Pt. and placed 2 cm. from the ionization chamber.

Since 1 mgm. of radium at 1 cm. gives an ionization equivalent of 8·4 r/hr.,

$$1 \text{ gm. at } 2 \text{ cm. gives:—} 8{\cdot}4 \times \frac{1{,}000}{4} = 2{,}100 \text{ r/hr.}$$

$$i.e., \ 1 \text{ R} = 2{,}100 \text{ r/hr.}$$

or it may be written as 1 r/sec. = 1·61 R.

Behnken and Jaeger[52] deduced an "ideal" value of the relation after very careful experimental investigations and their results in two series of experiments were 1 r/sec. = 1·60 or 1·62 R.

(*b*) THE D UNIT. The D unit of Mallet[53] was defined as the dose corresponding to the ionization effect of 100 mgm.-hours under certain conditions. These conditions were:—

The source is 10 mgm. of radium element, of 20 mm. active length, filtered by 1 mm. of platinum. The ionization is measured at a distance of 26·6 mm. from the centre of the radium.

The intensity at the point under consideration is determined by calculation (equation (2), p. 52) as 1·22 Imc. Thus in 10 hours (which is the time corresponding to 100 mgm.-hours) the dose is equivalent to 12·2 Imc.-hours.

$\therefore$ The D unit is equivalent to $12{\cdot}2 \times 8{\cdot}4\, r = 102{\cdot}5\, r$.

(*c*) THE MILLICURIE-DESTROYED (mc.d.) AT 1 CM. Some workers, particularly of the French school, prefer to work in terms of millicuries destroyed at 1 cm. distance rather than in terms of milligram-hours at 1 cm., the filtration being understood as 0·5 mm. Pt. Obviously the relation between these quantities is that (see p. 9)

$$\begin{aligned} 1 \text{ mc.d. at } 1 \text{ cm.} &= 132{\cdot}4 \times 8{\cdot}4\, r \\ &= 1{,}111\, r \end{aligned}$$

(*d*) THE SKIN ERYTHEMA DOSE. As we have already mentioned (p. 57) a dosage system based on erythema doses has been developed over a period of many years at the Memorial Hospital, New York, which has been widely used in America. It is therefore of great value to know the number of röntgens which produce the standard erythema dose that is used for this purpose. Fortunately, Mrs. Quimby, one of the workers very closely associated with this dosage system, has devoted some time to this relation quite recently.[10] Using data that had been obtained from three different small radium applicators, she found three values for the erythema dose (given in one irradiation) from a point source under the usual standard conditions of 1 cm. distance and 0·5 mm. platinum filtration, to be 123, 132 and 116 mgm.-hours, *i.e.*, an average of 123·7 mgm.-hours. The standard skin erythema dose in this case is defined as that amount of radiation which will, in three weeks, just produce a slight reddening or tanning of the skin in 80 per cent. of those treated. Using the factor 8·4 it follows that the average skin erythema dose of gamma rays is 1,039 röntgens, which should be a satisfactory conversion factor for transforming erythema doses into röntgens. Mrs. Quimby[10] has suggested that 1,000 *r* is a sufficiently accurate value to use, which simplifies the procedure considerably. " It should be emphasised however that this conversion factor refers only to gamma-ray doses, and for points in the tissue which are surrounded by at least 4 mm. of ' air-equivalent ' material. It does not refer to röntgen ray doses."[10]

14. The röntgen and Energy Absorbed

At the present time the majority of physicists concerned regard the röntgen as defined at Chicago in 1937 as a suitable and pertinent dosage unit for gamma rays, and we have seen that this attitude rests upon considerable experimental and theoretical evidence. It must be remembered, however, that in this method of dosage, one obtains a measure of the amount of radiation absorbed in a small volume of *air* situated at the point considered. The relation between the röntgens recorded and the *energy absorbed* by the *tissues* requires further consideration. It is the latter in which the clinician is really most interested. This relationship, as is being realised more and more, may be quite complex in a number of ways. A few workers indeed, consider it so complex, that they still regard the use of the röntgen for gamma ray dosage and its measurement by a small ionization chamber, as somewhat premature.[54, 39]

Among other things, the relation between the energy absorbed at a point in tissue and the röntgens measured at that point will depend upon the atomic number or numbers of the tissue surrounding the point and upon the homogenity and extent of these tissues. So far as the atomic numbers of the tissues are concerned, Mayneord[55] has shown that the substances most likely to be found in tissues have energy conversions very similar to that of air for wave-lengths below 50 X.U., and we have seen that the effective wave-lengths of the radiations used in radium therapy do not appear to exceed that value (p. 45). Wilson[56] has also shown that even for bone the energy conversion is only a few per cent. greater than that for air. It seems, then, that the possible effect of atomic number of the tissues will not be very great for gamma rays.

Since the measurement of dose in röntgens necessitates conditions of electronic equilibrium, brought about by sufficient extent of material around the point considered, the degree to which these conditions are fulfilled in the irradiation of biological material, is a most important consideration. The consideration of dosage at a point, measured in röntgens, necessitates the consideration of a finite volume of material having a radius of the order of several millimetres. Thus questions such as a rapid variation of dosage-rate from point to point[57] and the variation of density or discontinuity[56] of the medium become of importance. The question of discontinuity of the medium has to be considered especially in connection with the measurement of skin dosage. Some workers adopt the attitude that the röntgen is not suitable for the measurement of skin dosage in radium therapy, because in this case, owing to the change in medium from tissue to air, the conditions necessary for a measurement in röntgens are not fulfilled directly. However, if the skin surface is covered by a sufficient thickness of an " air-wall " material such as, say, celluloid, a measurement at a skin surface becomes comparable to one made at a depth. This point has been made by others.[10, 58] Whether it is preferable to be able to specify the dose by using such a cover, or to lower the skin dose by an uncertain amount by not using it, is a debatable point.

Difficulties are also likely to occur in the measurement of gamma ray dose in regions close to radium sources such as is often required in cases of intra-cavitary and interstitial irradiation. Here the complexity of rapid variation of intensity from point to point and that of insufficient material for electronic equilibrium may occur simultaneously. We have seen, however, that satisfactory measurements may be made as close as 8 mm. to a radium source, and Parker[58] has pointed out that the dosage-rate very close to radium sources is seldom of any great interest, since it is inevitable (see Chap. VI) that the values existing must greatly exceed those regarded as " the dosage value " for a radium implant.

A stage seems to have been reached, then, at which it appears possible to measure gamma rays in röntgens which bear a relation to the same unit as is used for X-ray dosage, by methods that are convenient for practical therapy. In view of the tendency for the methods of X-ray and radium therapy to come more closely into line, by the development of X-ray tubes excited at higher and higher kilovoltages on the one hand, and by the development of radium teletherapy on the other, this would seem to make for further progress. That it is but a stage, and not the end, is possibly indicated by the attitude, already mentioned, that is taken by some workers. Thus Sievert[39] regards the röntgen as a provisional unit, and he believes " that in the next few years radiological research will bring to light so many biological difficulties in estimating the effective dosage that the question of units will become of less importance." Results obtained by Failla[34] suggest that still further research is required since they seem to indicate that röntgen measurements do not always measure the biologically effective dose.

15. Physical Dosage Factors

Although it is generally realised that physical factors, other than total dose, affect the biological result that is obtained by irradiation, insufficient attention is paid to these other factors in statements of radiation technique. Innumerable radio-biological experiments and clinical studies have shown that apart from biological considerations, a number of purely physical factors influence the biological effects produced by high-voltage radiation. These factors are (*a*) the total dose of radiation (röntgens), (*b*) the dosage-rate (*r*/hr. or *r*/min.) for the individual doses, signifying the rate at which energy is delivered during each treatment, (*c*) the interval between successive irradiations, (*d*) the dose given at each treatment and (*e*) the overall time in which the total dose is delivered.

Whenever any statement of radiation dose is made, it should be regarded as incomplete unless all the factors are included in some form or other. The total overall treatment time is especially important as is made evident by the fact that whereas the skin erythema dose of gamma rays is approximately 1,000 *r* when the dose is delivered in a single irradiation (p. 79), some 6,000–7,000 *r* is needed to produce the same reaction when the radiation is spaced over a period of four to five weeks.

In concluding this chapter it must be pointed out that with the present limitations to our knowledge that still exist, when X-rays and gamma rays are both used in the treatment of a lesion, it cannot be assumed that the simple sum of the X-ray röntgens and the gamma ray röntgens adequately expresses the tissue dose. The evidence available indicates that quite different numbers of X-ray röntgens and gamma ray röntgens are required to produce the same biological reaction ; this is particularly definite in the case of the production of a skin erythema. Furthermore, it has been shown that in the production of a skin erythema, doses of gamma rays and röntgen rays are not strictly additive.[59, 60] It requires more of a combination of the two in equal parts than of either alone. For other human tissues little definite information is available. In view of this difficulty the Standardisation Committee of the American Radium Society[61] has suggested that the gamma ray röntgen be written r_γ while for the X-ray röntgen the subscript *ν* is omitted. Such a procedure would undoubtedly guard against a careless, loose, and possibly inaccurate use of the unit until our knowledge is more certain.

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CHAPTER IV

GAMMA RAY DOSIMETRY—APPARATUS FOR DOSAGE MEASUREMENT

THE various instruments used for the measurement of gamma ray dose consist primarily of apparatus designed to measure the very small ionization currents generated by the radiation in ionization chambers designed and constructed in accordance with the principles and conditions we have seen it is necessary to fulfil. Two main methods have been used to make such measurements. In the first of these methods the ionization chamber is mounted at the end of a suitable lead system which leads the ionization current to the apparatus designed to measure it. We shall refer to this as the "chamber-lead" method. In the second method, leads are dispensed with entirely and the ionization chamber takes the form of an air condenser which exists independently of any other apparatus, but whose loss of charge may be measured by means of an electrometer. This method is now usually referred to as the Sievert condenser chamber method.

1. Instruments of the "Chamber-Lead" Type

Lead and Ionization Chamber. Because gamma radiation has such a great power of penetration and because the ionization currents to be measured are relatively small, the construction of a suitable lead to convey the ionization current from the ionization chamber to the current measuring apparatus, requires special attention. In order that the lead may be earth-screened, it is usually carried through a metal conduit and is mounted at intervals upon a material that is highly insulating. For this purpose "amberoid," a form of amber which may be obtained in cylindrical rods, is most commonly used, although materials such as quartz or red sealing wax are suitable. Amberoid machines quite satisfactorily with very sharp tools, and after suitable polishing of the outer surfaces, is very highly insulating. To remove the possibility of losses due to ionization within the lead, the best procedure is to construct the lead so that it is air-tight and then to maintain it constantly evacuated by means of a suitable pump. A "Hyvac" oil pump serves the purpose extremely well. Some authors have filled the lead with an insulating solid medium which may be poured in its liquid form, such as ceresin wax. It is our experience, however, that an evacuated lead is far superior since the wax-filled types are difficult to repair or modify, and often seem to give rise to erratic electrical effects due to some kind of "soaking" action in which charge appears to accumulate in the wax.

The size of the ionization chamber, which chiefly determines its design, depends upon the type of measurement for which it is intended. The closer to a radium source the chamber has to be used, the smaller it will need to be for accurate measurement. It has been pointed out by Gray[1] that as a rough general rule, the chamber should be of such dimensions that the extremes of gamma ray intensity throughout the air volume do not differ by more than 30 per cent. Under these conditions the observed ionization is a measure of the gamma ray intensity at the centre of the air volume to an accuracy at least as good as 2 per cent. On this basis we may calculate the maximum internal linear dimensions of ionization chamber that should be used at different distances from a single radium source; the values are given in Table 11.

TABLE 11.—*Relation between Maximum Dimensions of Chamber and Distance from Radium Source of the point of Measurement*

Distance from radium	0·5 cm.	1·0 cm.	1·5 cm.	2·0 cm.	5·0 cm.	10·0 cm.
Maximum diameter of air volume of chamber.	0·7 mm.	1·3 mm.	2·0 mm.	2·6 mm.	6·8 mm.	12·8 mm.

In practical measurements of dosage in therapeutic techniques one is concerned usually with distributions of radium for which the rate of variation of intensity is smaller than for a single source, so that larger dimensions can then be used. Further observations upon the size of ionization chamber and its accuracy have been made by La Touche and Spiers.[2]

For measurements in a phantom, as distinct from those in air, it is not essential to have the wall thickness of equilibrium value.

This permits a closer approach to the source, especially if it is within the phantom, but it is doubtful whether the measurement may be expressed in röntgens. If such a thin-walled chamber is used, it may be adapted for measurements in air by the addition of an outer jacket of the required thickness.

Typical chambers for dosage measurements by this method are illustrated diagrammatically in Fig. 37. The wall material of the chamber may be any of those listed in Table 9 (p. 71). For measurements of very low dosage-rates, such as arise in protection considerations, it is necessary to use quite a large chamber with an air volume of the order of a litre or more in order that the total ionization current may be of suitable dimensions. In this case a long evacuated lead can no longer serve its purpose of removing the measuring apparatus to a distance from the seat of the radiation, so that the chamber may be connected almost directly to the current measuring system. Also, the space rate of variation of intensity is usually very small so that the large chamber does not introduce any serious errors. In all cases, sufficient potential is applied to the

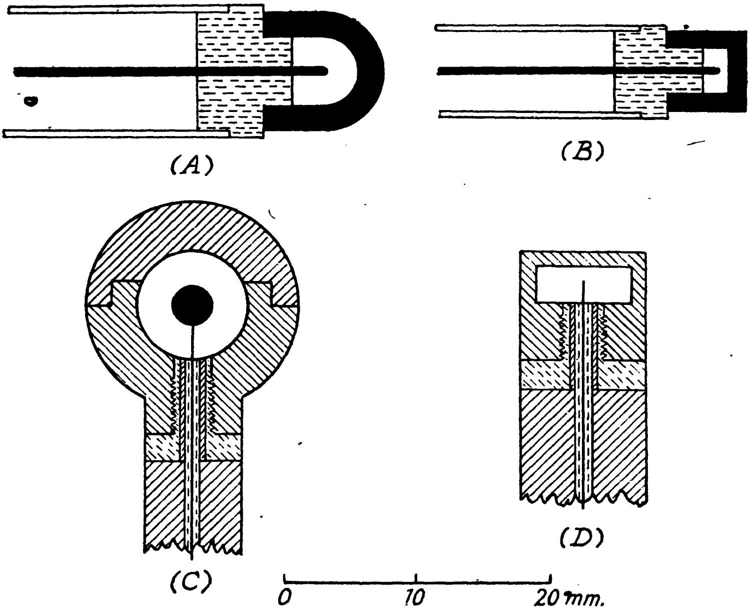

FIG. 37.—Some typical ionization chambers. Types C and D are due to L. H. Gray.[1]

chamber to ensure that saturation current is measured. The value of this depends upon the air gap in the chamber and the intensity of the radiation being measured.

The sensitivity of the current measuring system required for measuring the ionization currents, depends upon the magnitude of the currents. This in its turn is determined by the air volume of the chamber and the dosage-rate at the chamber. Since a dosage rate of 1 *r*/min. gives rise to an ionization current of $5{\cdot}56 \times 10^{-12}$ ampères in a chamber 1 c.c. in volume, we may calculate the order of magnitude of the currents to be measured. Table 12 shows the approximate ionization currents to be expected in measurements connected with various aspects of radium therapy. These values are deduced from the order of dosage-rate usually used and the approximate size of chamber suitable for the measurement.

TABLE 12

Type of radium therapy	Range of dosage-rates	Air volume of chambers	Range of ionization currents
Interstitial and intra-cavitary irradiation.	0·2–2·0 *r*/min.	0·05–0·1 c.c.	$5{\cdot}6 \times 10^{-14}$–$1{\cdot}1 \times 10^{-12}$ ampères
Surface, plaque irradiation.	0·1–1·0 *r*/min.	0·1–1 c.c.	$5{\cdot}6 \times 10^{-14}$–$5{\cdot}6 \times 10^{-12}$ ampères
Teletherapy	0·5–10 *r*/min.	1 c.c. approx.	$2{\cdot}8 \times 10^{-12}$–$5{\cdot}6 \times 10^{-11}$ ampères
Protection measurements.	10^{-5}–10^{-3}*r*/sec.	1 litre approx.	$3{\cdot}3 \times 10^{-12}$–$3{\cdot}3 \times 10^{-10}$ ampères

CURRENT MEASURING SYSTEMS. (i) *Utilising an Electrometer.* By far the most common method of measuring the ionization current is to use some form of sensitive electrometer. In this country the Lindemann electrometer, the sensitivity of which may be varied quite readily over a wide range, is very frequently used; it is small, robust, stable, and does not require any complicated adjustments.

The simplest method of measurement is to allow the insulated needle of the electrometer, which is connected to the lead from the ionization chamber, to accumulate the incoming charge. Then, if the rate of increase of potential is measured by the electrometer, the current may be deduced if the electrical capacity of the system is known, or a calibration may be made using a known dosage-rate, so that an absolute value of the capacity is not involved.

A more accurate and reliable procedure is to use the Townsend balance method. The principles of this method may be illustrated by reference to Fig. 38, which depicts a typical apparatus for the measurement of gamma rays. The insulated needle of the electrometer is connected to the insulated plate of a capacity C of the order of a few centimetres and to the lead from the ionization chamber. The other plate of the condenser is connected to a potentiometer P, so that its potential may be varied continuously to a value which is read by the voltmeter V. At the beginning of a measurement the potential of the insulated system is zero (earthed). The system is isolated and electric charge accumulates on it at a rate depending upon the ionization current. The potential on the other plate of the condenser is then continuously increased to balance out the incoming charge and so to keep the electrometer needle in its zero potential position. The number of volts V, thus applied in a time t seconds, is read on the voltmeter; the ionization current i is given by :—

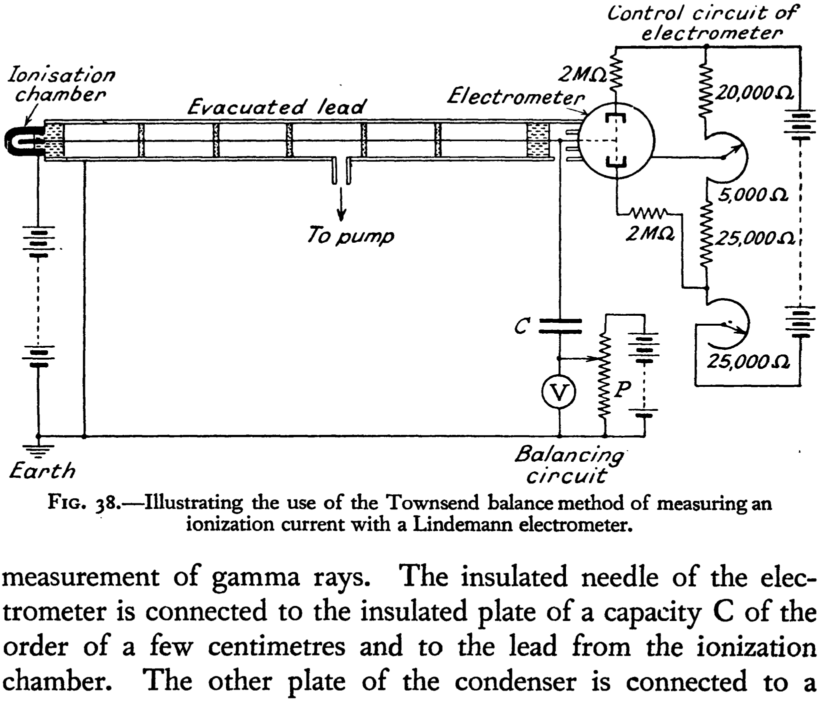

FIG. 38.—Illustrating the use of the Townsend balance method of measuring an ionization current with a Lindemann electrometer.

$$i = C. \frac{V}{300} \cdot \frac{1}{t} \text{ e.s.u./sec.} \quad \ldots \ldots \quad (1)$$

If the volume of air within the chamber is v c.c., i/v is a measure of the number of röntgens per second.

In practice measurements should be made with both positive and negative chamber potentials. The mean of these values gives a value free from errors due to stray ionization. Advantages of this method are that it is a null method and the potential difference between the lead and the earthed screening tube is always maintained at zero. The control circuit of the Lindemann electrometer shown in Fig. 38 has been described by Grimmett[3] and is extremely useful. By means of this it is possible to change the sensitivity very quickly while a simple zero control is also available.

If the current to be measured is sufficiently large, say not less than 10^{-11} ampères, it is possible to make the instrument direct reading by connecting a high resistance of the order of 10^{10}–10^{11} ohms between the lead and earth. The steady potential (of the order of 1 volt) which is then built up across the ends of the resistance, may be measured as a steady deflection on the electrometer. When used in this fashion it is preferable to calibrate the instrument by measuring the deflection for a known dosage-rate.

Various high resistors have been developed which prove satisfactory for this purpose such as a pencil line on amber[4] and liquid mixtures in glass,[5] and recently the S. S. White Dental Manufacturing Co. has marketed composition resistors of suitable values which have been used and found quite satisfactory.[11]

(ii) *Utilising Electrometer Valves.* In order to obtain great sensitivity, the Townsend balance method may be used in conjunction with an electrometer valve which replaces the electrometer as the indicator of balance. Electrometer valves are available with three or four electrodes as, for instance, the electrometer triode type "T" (or E.T.1) made by the British G.E.C.[6] and the F.P. 54 produced by the G.E.C. Schenectady, U.S.A. which has four electrodes, anode, filament and two grids. The essential feature of the electrometer valve is that one of the electrodes is a grid of very high electrical resistance, of the order of 10^{16} ohms, which enables it to be used as an electrometer. To attain this result the valves have certain special features, one of which is that the controlling potentials are of the order of 4–6 volts only, in order to avoid collision ionization.

The four electrode type has the advantage, as Du Bridge and

Brown[7] have shown, that one valve may be used in a bridge circuit such that fluctuations due to any small changes which may occur in the supply batteries, are automatically balanced out. The space-charge grid is at positive potential, while the control grid (to which the ionization current is fed) is negative. If the potentials of filament, space-charge grid, anode and control grid are all supplied by a common potentiometer and battery arrangement, the fluctuations in the battery voltage will affect all the potentials simultaneously and by proportional amounts. Since changes in the space charge grid affect the emission current in the opposite sense to the others, the changes may be made self-compensating by a suitable choice of potentiometer tapping points. If a very sensitive galvanometer is used in the bridge, because of the amplification of the valve, an extremely sensitive instrument is available. Gray[8] has referred to the use of this circuit in which he obtains a sensitivity of approximately 1 mm. galvanometer deflection for 0·1 mV change of grid potential of the valve. The main elements of this type of circuit are illustrated in Fig. 39. In actual use it is

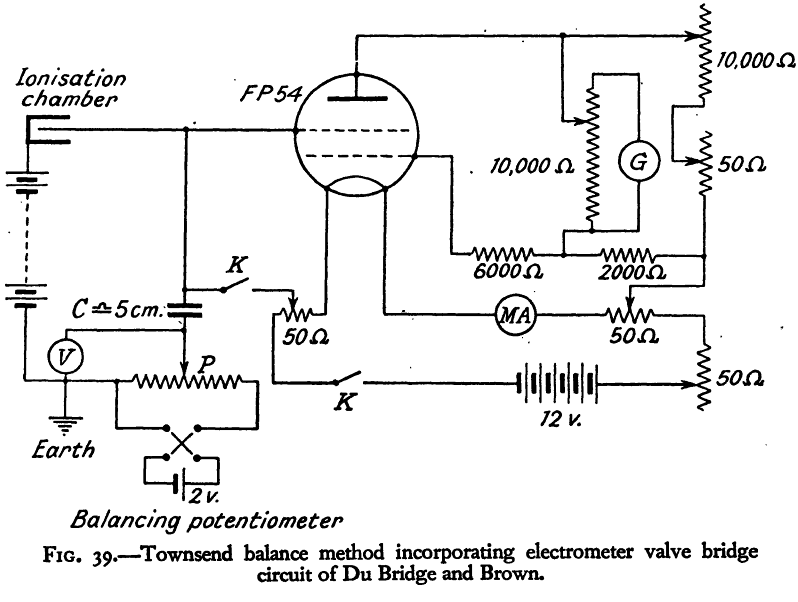

FIG. 39.—Townsend balance method incorporating electrometer valve bridge circuit of Du Bridge and Brown.

necessary to have the valve contained in a dry evacuated box to avoid ionization losses and to serve as an earthed screen; this box and the lead can form one complete evacuated system. If the

Townsend balance method is not used, but rate of accumulation of charge is measured as rate of drift of the galvanometer, even higher sensitivities may be obtained, although the order of accuracy is less. It is claimed that currents as small as 10^{-16} ampères may be measured in this way. A similar circuit has been described by Friedrich, Goldhaber and Griffith[9] which uses two, four-electrode electrometer valves " T 133 " (made by the German firm A.E.G.), one in each arm of the bridge.

A disadvantage of the above circuits from the point of view of practical, everyday work, is that they are not robust and simple enough to permit of great portability, and this is often required. In this connection Lea[10] has described a valve circuit which has all the advantages of the Townsend balance method, but which registers the final measurement upon a milliammeter, across which the pointer travels at a rate depending upon the magnitude of the ionization current. In this instrument the ionization current is fed to the grid of an electrometer triode type " T " and the output from this is amplified by further valve stages in such a manner that automatic balancing is obtained. The instrument functions as an integrating meter, reading in units of 0·1, 1·0 or 10 electrostatic units.

It will be seen that none of the methods of measurement referred to so far are direct reading. To obtain this property it is usually inevitable that some accuracy is lost, but for practical clinical work it is hardly essential to have a very high order of accuracy since the conditions of actual treatment, more often than not, themselves cannot conform to such accuracy.

A simple circuit, based on a three-electrode electrometer valve, has been investigated by Kaye and Bell.[5] This is designed to give a direct reading of the dosage-rate. It is eminently suitable when the current to be measured is of the order of 10^{-10} to 10^{-11} ampères. The essential elements of the circuit are shown in Fig. 40. The ionization current is passed down a high resistor R of the order of 10^{10} to 10^{11} ohms and the resulting steady potential across the resistor reduces the effective negative bias applied to the grid of the valve, so that a change of anode current is recorded upon the microammeter. Thus, if the negative grid bias applied to the valve has a suitable value, the microammeter reading may be made proportional to the dosage-rate. The high resistance used by

Kaye and Bell was a mixture of benzol, alcohol, picric acid and phenol, and its value was very little affected by temperature changes.

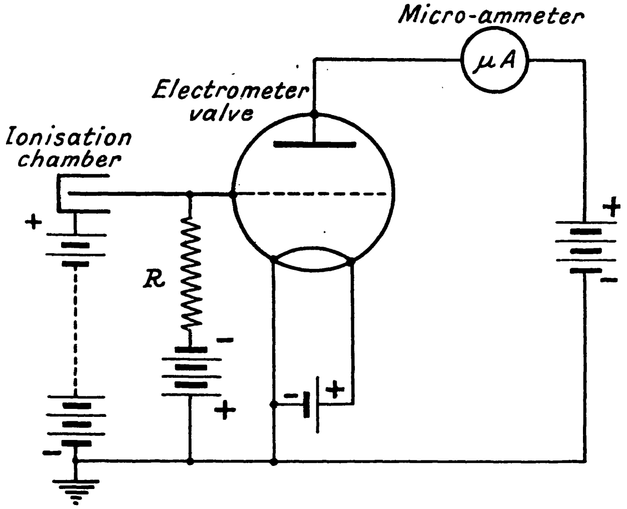

FIG. 40.—Essentials of single valve, direct-reading dosage-rate meter. (*Kaye and Bell.*)

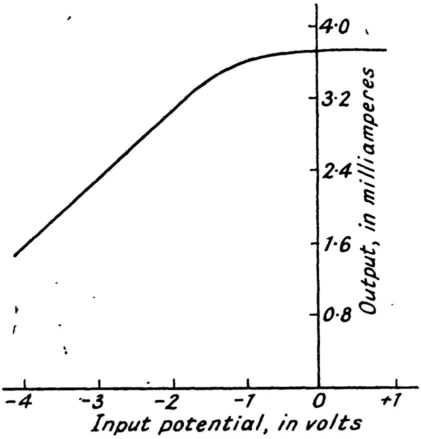

FIG. 41.—Input–output characteristic of three-valve dosage-rate meter. (*Langmead.*)

A barretter is included in the filament circuit of the valve to help maintain the filament current at a steady value.

More recently Langmead[11] has investigated the possibility of using the direct reading principle for the smaller ionization currents

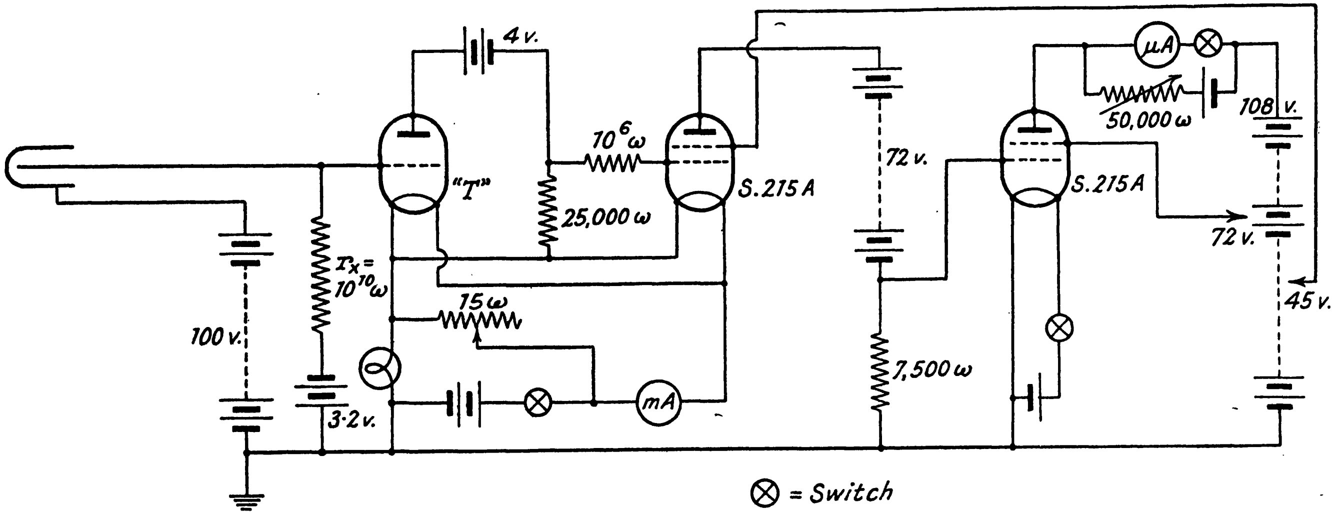

FIG. 42.—Circuit of direct-reading dosage-rate meter incorporating a direct-current valve amplifier. (*Langmead.*)

we have seen to arise in daily practice. The circuit he has developed consists of a three-electrode electrometer valve, type " T," followed by two further stages of direct-current amplification. In this way an amplification of the order of 10^6 was obtained and, as may be seen from the input-output characteristic of the amplifier, a change of 1 volt in the input voltage of the electrometer valve corresponds to a change in current output of about 800 microampères (see Fig. 41). The variation in input voltage is brought about by the potential built up by the ionization current across the high resistor (10^{10}–10^{11} ohms). The main anode current flowing in the circuit being balanced out by means of an auxiliary circuit, the output obtained in micro-ampères when the ionization current flows, is proportional to the dosage-rate provided the linear range shown in Fig. 41 is not exceeded. The circuit of this instrument is given in Fig. 42, and Fig. 43 is a photograph of it as it is used

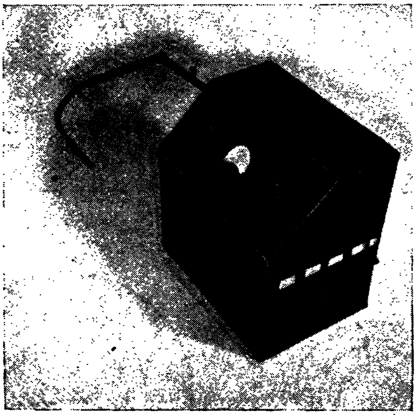

FIG. 43.—Practical form of three-valve dosage-rate meter. (*Langmead.*)

at Westminster Hospital. The grid bias of the electrometer valve is maintained by three Weston Standard Cadmium cells and a novel feature of the instrument (see Fig. 43) is that part of the evacuated lead is flexible,[11] which permits some degree of movement of the ionization chamber while the set itself remains stationary.

In the construction of the apparatus it has been found convenient to use the composition high resistors manufactured by the S. S. White Dental Manufacturing Co. for the first stage of the circuit.

These have been mounted in wax-filled, metal cases, which may be screwed into the side of the evacuated metal box carrying the electrometer valve. In this way various resistance values can easily be applied to the control grid of the valve, so that a range of sensitivities may be obtained in this manner, in addition to modifications in the size of the ionization chamber. It must be said that provided due precautions are taken, the simple circuit forming the basis of this instrument behaves unexpectedly well with regard to zero drift, stability and accuracy, so that it forms a valuable part of the equipment of a radium physics laboratory.

2. The Sievert Condenser Chamber Method

Condenser Chambers. The leads connecting the ionization chamber to the current measuring system often form a source of considerable difficulties, especially when the possibility of direct measurements on and within patients has to be considered. They

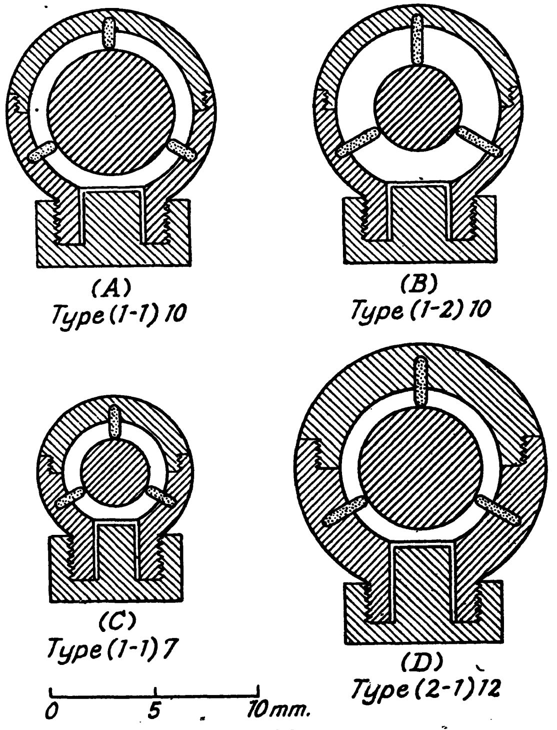

FIG. 44.—Some types of spherical Sievert condenser chambers.

are indeed often the source of considerable experimental difficulty even without this added consideration. The condenser chamber method very successfully surmounts this difficulty simply by removing all leads, and so constructing the ionization chamber, that it takes the form of a condenser with air as the dielectric, the outer wall being continuous and at earth potential, while the inner electrode is usually raised to a high potential of several hundred volts.

This method had been used by Glasser and his co-workers[12, 13] in 1928, but in 1932 Sievert[14] gave an exhaustive account of his development of the method for the measurement of most of the ionizing radiations. Using mainly elektron metal as the chamber material and amberoid for the insulation, Sievert designed many types of small condenser chambers, the beauty of which design is possibly only excelled by the craftsmanship of the instrument makers (Gustaf Rose & Co., Stockholm) who constructed them to Sievert's specification.

A few of the more common types of chamber originally described by Sievert are illustrated in Fig. 44. These chambers are perfectly spherical, their sensitivity depending upon the electrical capacity and air volume, which in their turn are determined by the over-all dimensions and air gap. They consist of a solid, spherical, inner electrode which is concentric with the outer spherical wall and insulated from it by four small amber pegs mounted in the outer wall. For purposes of reference Sievert describes the chambers by the letterings shown in Fig. 44. Thus the chamber of Fig. 44 (A) is referred to as (1–1)10. This means, in the order of the figures, that the wall thickness is 1 mm., the air gap is 1 mm. and the external diameter is 10 mm. The chamber is thus completely specified. If a greater wall thickness is required it may be obtained by adding an additional shell of the required thickness. The outer wall is constructed in two halves which screw together and access to the inner electrode is obtained by unscrewing the small cap. Similar chambers have been constructed in celluloid coated with graphite, and Zimmer has been responsible for some made of aerion (see Chap. III) which were produced by the P.T.W. of Freiburg. The latter have the advantage that they may be used for X-ray as well as gamma ray measurements, but in our experience they are not nearly so robust or so well insulated as those of Sievert.

Many other types of condenser chambers have been described by Sievert, and Grimmett,[15] Wilson,[16, 17] and Spiers [18] have described chambers which are easier to construct than the spherical pattern, but are usually less symmetrical. Some of these are illustrated in Fig. 45.

For its success the condenser chamber method depends upon extremely good insulation, and for this purpose amberoid has been most used. To obtain the required degree of insulation the amberoid insulators must be polished and dried most carefully and all dust and fluff must be removed. The polishing is done with various grades of emery cloth down to the very finest "blue-back" paper and this followed by metal polish or fine amber dust. When mounted in position, dust is removed from the surface of the insulators by vigorous blowing with dry air, and finally they are

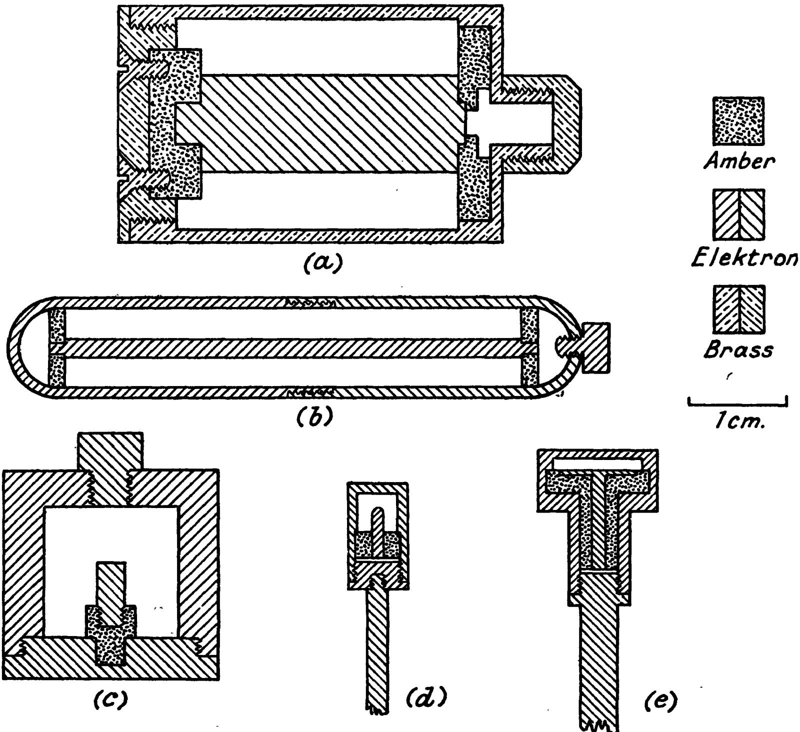

FIG. 45.—Various types of condenser chambers: (*a*) For protection measurements (*Grimmett*), (*b*) for protection measurements (*Wilson*), (*c*) for low dosage-rates (*Wilson*), (*d*) and (*e*) for interstitial measurements (*La Touche and Spiers*).

dried in a desiccator in which it is advisable to keep the chambers when they are not in use. By this treatment amazingly good insulation may be obtained and many of Sievert's original chambers lost less than 5 per cent. of their charge over a period of more than one month. Obviously natural losses during actual measurements are entirely negligible.

Use of Chambers with the Wulf Electrometer. For the measurement of the ionization in condenser chambers, some form of electrometer is used. The Wulf[18] bifilar electrometer is most useful for this purpose and has been widely used. It has a great advantage in that it is completely independent of controlling batteries while its capacity (of the order of a few centimetres) and its sensitivity (approximately 3 volts per scale division) make it well suited for use with condenser chambers if they are charged to a potential of a few hundred volts.

In actual use the ionization current within the chamber is determined by measuring the original potential V_0 to which the chamber is charged and the final potential V' after it has been exposed to the radiation for a time t secs. Then, if the potentials are measured in volts we have :—

$$\text{r/sec.} = \frac{C}{v} \cdot \frac{V_0 - V'}{300} \frac{1}{t} \quad \ldots\ldots \quad (2)$$

where C is the capacity of the chamber in centimetres and v is the air volume in cubic centimetres. It is more common, however, to calibrate the chambers by means of a known dosage-rate at a known distance from a standard source. It is then unnecessary to know the absolute values of C and v.

The potentials V_0 and V' are obtained indirectly by sharing the charge of the chamber with the electrometer, which is initially at zero potential. The deflection thus obtained on the electrometer, which may be converted to volts by means of the linear calibration curve of the instrument, is related to the actual potential of the chambers as follows :—

If C is the capacity of the condenser chamber and V_0 its potential in volts, while C_0 is the capacity of the electrometer and V_1 is the common potential of chamber and electrometer when the charge has been shared, then :—

$$C V_0 = (C + C_0) V_1$$

$$\text{or } V_o = \frac{C + C_o}{C} V_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Thus, if $\frac{C + C_o}{C}$ is known, the sharing potentials may be converted into the true chamber potentials quite readily. Since $\frac{C + C_o}{C} = \frac{V_o}{V_1}$, its value may be determined very easily by means of the sharing process itself.

The process of charging and sharing of charge is considerably simplified if the Wulf electrometer is fitted with a mercury switch system as is illustrated in Fig. 46, and has mounted upon it suitable seatings to hold the chamber during the process. By means of

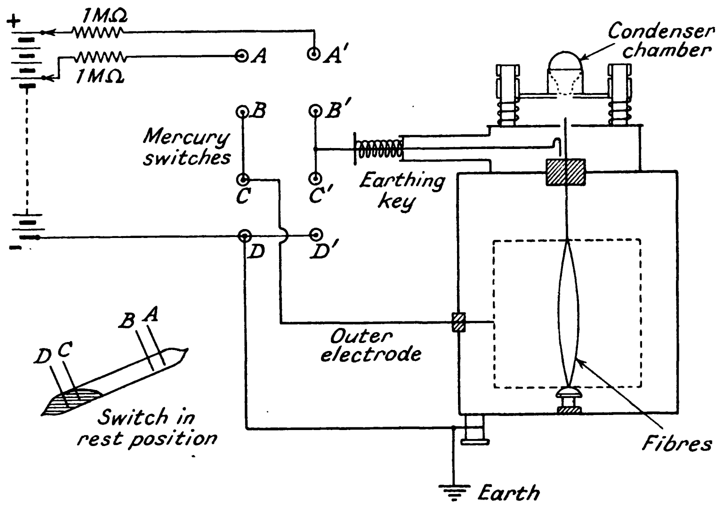

FIG. 46. The use of a Wulf electrometer in a circuit enabling the electrometer to be used directly for charging condenser chambers as well as for the measurement of the charge carried by the chambers.

this circuit, the fine, stiff lead from the strings of the electrometer may be put to a high potential, or to earth potential, simply by throwing over all the mercury switches simultaneously. The chamber may therefore be charged by depressing it to make contact when the lead is at the high potential, and its charge may be shared with the electrometer when the lead has been earthed and isolated. After irradiation, of course, only the sharing process is necessary to obtain the final potential V′. It is usual to adjust the exposure time so that $\frac{1}{2}$–$\frac{2}{3}$ of the original charge is lost and, of course, the final potential must be sufficient still to ensure saturation.

Use of Chambers with the Lindemann Electrometer. When the air gap of a condenser chamber is small, as it commonly is, the potential required for saturation is fairly low, so that in order to accelerate the measurement of low dosage-rates, it may be an advantage to work at lower charging potentials and with smaller potential differences. This necessitates a more sensitive electrometer and the Lindemann electrometer may be used quite well if suitable arrangements are made.

(i) In this connection the author has provided a Lindemann electrometer with a switching system which enables one to carry out the charging and sharing processes in a manner identical to that used with the Wulf electrometer.[19] The essentials of this circuit are illustrated in Fig. 47. The electrometer is used in a normal manner. When the three mercury switches (ABCD, A′B′C′D′, and A″B″C″D″) are in their rest position contact is made between the points C″D″ and the needle of the electrometer by the spring plunger S. The needle is then earthed and the controlling potentials are applied to the plates of the electrometer. Thus, if the plunger S is released, the charge on a chamber

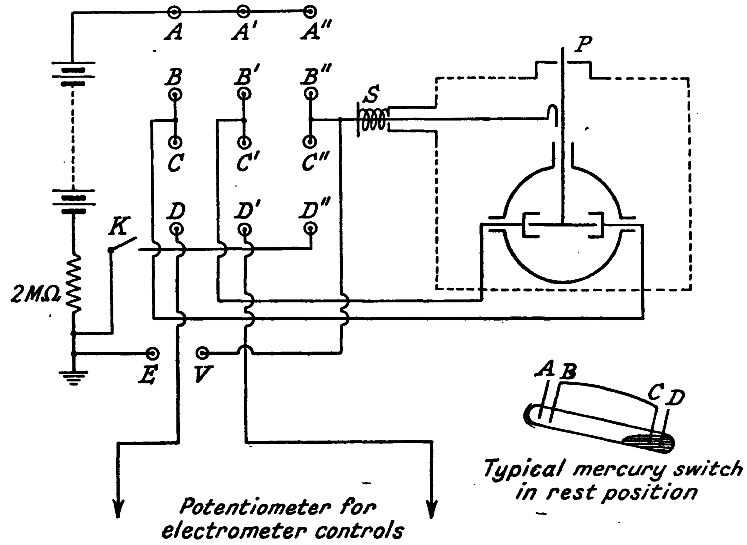
A
A′
A″
P
B
B′
B″
S
C
C′
C″
K
D
D′
D″
2MΩ
E
V
A B
C D
Typical mercury switch in rest position
Potentiometer for electrometer controls

FIG. 47. Lindemann electrometer circuit for use with condenser chambers.

may be shared with the electrometer and the resulting potential measured. If the three switches are thrown over so that contact is made simultaneously between AB, A′B′, and A″B″, while contact between CD, C′D′ and C″D″ is broken, the controlling potentials are removed from the electrometer, and by pushing in the plunger arm, the electrode is raised to the charging potential supplied by the battery. The chamber may then be charged in the same way as with the Wulf electrometer. The sensitivity of the electrometer may be measured and adjusted whenever required by opening the key K, and applying a known potential between E and V, which in turn is applied to the electrometer needle by means of the plunger S.

(ii) La Touche and Spiers[2] have described another circuit which uses the Lindemann electrometer for condenser chamber measurements. It is illustrated in Fig. 48. In this circuit a direct deflection method is used and the operation of charging the condenser also checks the sensitivity of the electrometer system. The electrometer is insulated and its case is raised to 60 volts above earth potential by means of the battery B. The potentiometer P applies a further 3 volts to the electrometer needle and to the condenser charging pin through an insulated key K_1, operated by a small pneumatic bulb. The other insulated key K_2, connects the needle to the case for safety when adjusting battery potentials. The voltmeter V ensures that a standard potential of 3 volts is applied to the electrometer needle, and it is arranged that this gives a full-

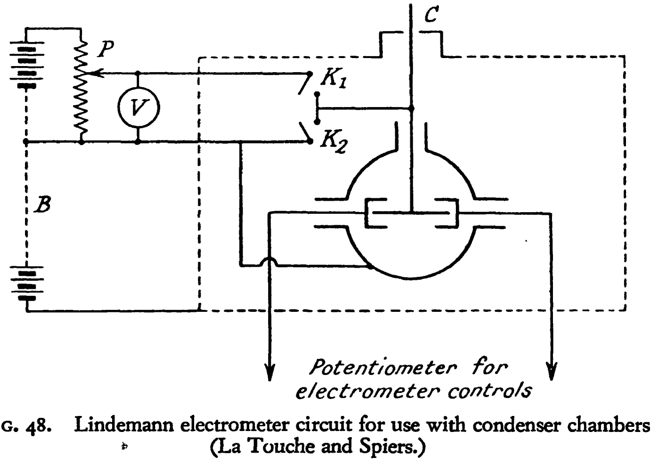

FIG. 48. Lindemann electrometer circuit for use with condenser chambers. (La Touche and Spiers.)

scale deflection by means of the sensitivity controls of the electrometer. The full potential applied to the charging pin C is then 63 volts. After exposure the electrometer is recharged through K, and its charge shared with the residual charge on the condenser. The circuit may be used conveniently by using a known radiation intensity and obtaining a calibration curve which relates the dose in röntgens to the electrometer deflection for a specific condenser chamber. The potential applied to the electrometer case by the battery B determines the maximum dose which can be measured by the condenser chamber, but does not affect the slope of the calibration curve appreciably. For great accuracy this potential is measured with a precision voltmeter.

In using these lower potentials, the effect of contact potentials becomes more serious, but it is not excessive for most clinical measurements.

Use of Chambers with Electrometer Valves. Another instrument for use with small condenser chambers, based upon an electrometer valve, has been described by Farmer.[21] The circuit of this is shown in Fig. 49. This instrument gives a direct reading on the dial of a meter as a measure of chamber voltage (negative

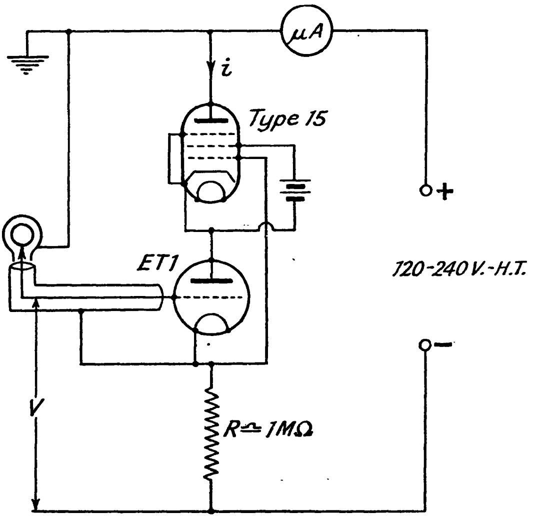

Fig. 49. Valve electrometer for the measurement of voltage on small condenser ionization chambers (Farmer). A common 2-volt source is used to operate the filaments of both valves). V, R and i are related very nearly by $i = \frac{V}{R}$.

with respect to the case) and is of a very robust nature admirably suited to measurements in a hospital radium department.

The voltage on the chamber, which is applied to the highly insulated grid of the valve, is measured in terms of the valve current. It is possible to apply the full chamber potential to the grid because the working range of the valve is extended and this permits the use of a large degree of negative feed-back which has the advantage of rendering the whole measuring system relatively independent of supply voltage and variations in the valve characteristic. The second valve (a 2-volt valve, type 15) is included so that the feed-back may be provided satisfactorily and the cathode resistance, of the order of 1 megohm, is employed to limit the maximum current through the valve to about 100 micro-ampères.

In order to arrange that practically the whole of the chamber voltage appears at the grid, so that the feed-back is as effective as desired, the capacity to earth of the grid and the grid lead is reduced to a small fraction of its original value by surrounding the valve and grid-lead by a screen connected to the electrometer valve filament; the potential of the latter follows very closely that of the grid itself.

A magnetically operated switch is used for "earthing" the grid of the electrometer valve before it is contacted with the ionization chamber.

The apparatus is not harmed by applying greatly excessive charges to the valve grid as may happen in experimental work. This is a very useful feature.

A method of using condenser chambers in conjunction with the four electrode electrometer valve F.P.54 has been reported[20] but full details are not yet available.

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CHAPTER V

RADIUM THERAPY WITH SURFACE APPLICATORS (PLAQUES)

1. In the surface method of radium therapy the radium sources are mounted at a short distance from the skin. The actual distance between the radium and skin surface that is used depends upon the depth below the surface to which it is desired to deliver an adequate dose of radiation. In practice, because of the quantities of radium that can be used and the difficulties of mounting the sources, it is seldom useful to use " radium-skin " distances greater than about 4 cm.

In common with the other methods of radium therapy, early treatments with surface applicators were purely empirical: clinicians administering treatment distributed the radium sources more or less intuitively, and learned from experience and observation just how much treatment the skin would tolerate from given applicators. Some time before any attempt was made to establish a dosage unit for gamma rays, investigations were made of the relative quantities of radiation available from different sources. Some of the earliest work of this kind was that of Friedrich and Glasser[1] who determined the " isodose " curves around radium containers of various lengths by means of a small ionization chamber. Further data was obtained later by other workers using ionization chambers as small as they could construct, notably Mallet,[2,3] Kessler and Sluys[4] and Stahel.[5] We have seen that similar information may be deduced by mathematical calculation (Chap. III). With such data at one's disposal, it is theoretically possible to deduce the dosage conditions for any surface applicator that may be constructed whether it is of regular or irregular shape, and whether it be plane or curved. Each case of this sort, however, constitutes an individual problem as may be seen from the work of Mallet[3] or Murdoch, Stahel and Simon,[6] who published studies of the dosage distributions for various individual arrangements of radium sources on surface applicators. An alternative method is to determine the dosage distribution due to each complete applicator by means of measurements with a suitable ionization chamber.

What is really needed for application to radium therapy by surface applicators, is a solution of the general problem of how to arrange radium sources, upon any surface applicator of specific shape and size, in order to obtain certain predetermined conditions of dosage-rate and homogeneity of radiation. This solution cannot well be worked out experimentally because the preparation of the necessary applicators and the making of the minimum number of measurements on each of these is impracticable in a busy department. For this reason the solution has been sought, and realised, (to sufficient accuracy for average clinical purposes) in the mathematical method.

Although it is perhaps not realised so generally as should be, with the information that is available now, it is possible to distribute radium for surface application by means of fairly simple rules so that a known degree of homogeneity of radiation exists over the irradiated area, whilst the dosage-rate is also predetermined. The distinct advantages of such methods over those which distribute the radium intuitively are: (i) It is ensured in advance that the irradiated area receives a uniform dose, (ii) Physical conditions may be reproduced more or less accurately from case to case and dosage may be controlled throughout the treatment, and (iii) The dosage-rate for the whole surface may be checked by means of a few direct measurements instead of an extremely large number of measurements.

In practice the clinician decides that he wishes to treat a certain area, when the problem from the point of view of the physicist becomes that of arranging to irradiate the area homogeneously at a known dosage-rate. Some of the methods devised to solve such problems, and the application of the methods to practical therapy, form the main subject-matter of this chapter.

2. Relation between Surface Dose, Area of Applicator and Quantity of Radium

One of the earliest attempts at a solution of the general problem of the dosage from surface applicators was made as long ago as 1922 by Mrs. Quimby[7] at the Memorial Hospital, New York. At that time it was not possible to concern oneself with the question of homogeneity of the surface dose so that only the amount of radiation delivered at the centre of an applicator was considered.

By considering each source upon an applicator as divided up into a number of small parts such that each part could be considered as a point source, it was possible to determine the total dosage at a point due to any complete applicator, due allowance being made for the filtration of each part. In this way it was possible to determine the relative amounts of radiation delivered at the centre of the skin area under the applicator, by a constant amount of radium or radon, distributed uniformly in tubes of various lengths, over circular, square and rectangular applicators of various areas, for several filtrations and for any radium-skin distance from 1 to 10 cm. The results obtained contain data for some 200 practical applicator sizes and distances, and information for any applicator not actually included can be obtained by interpolation.

The results of this work have been used mainly in conjunction with the skin erythema reaction. If the number of milligram-hours required to produce the erythema for any one of the applicators is known, that for any other applicator can be determined. The work thus enabled radiologists to compare doses delivered on the skin by various applicators and to express these in terms of the erythema dose. The results however are not strictly applicable to irregularly shaped applicators or curved surfaces.

3. Distribution of Radium for Homogeneity of Radiation and known Dosage-rate

With the development of the mathematical approach to the problems of the surface applicator, it has been possible to pay attention not only to the magnitude of the dose delivered, but also to the homogeneity of the dose over the treated area. Further, the expression of gamma ray dosage in röntgens has made it possible, in a way that now seems fairly free of ambiguity, to link up the dosage from surface applicators with that delivered by other methods of radium therapy.

Because of its relatively simple character and its applicability to a wide variety of cases, considerable attention has been given to the plane circular type of applicator.[8,9] Some of this investigation was described in Chapter III. By means of further study of such applicators Paterson and Parker[10] have been able to devise a system for the distribution of radium upon surface applicators of other regular shapes, such that uniformity of radiation, sufficient for average clinical purposes, is provided at a known mean dosage-rate.

The attainment of perfectly uniform irradiation would introduce tremendous difficulties, and for this reason " uniformity " is taken as not having variations greater than ± 10 per cent. This degree of uniformity is quite satisfactory clinically.

Parker[11] has pointed out that " the choice of ± 10 per cent. was entirely arbitrary, and as it would be theoretically possible to reduce the tolerance almost to zero, it has to be determined whether other considerations warrant such a variation." In the same article Parker deals with a number of instances of these other considerations and the errors they may introduce. One of the most important considerations relates to the mechanical difficulties in placing radium sources at the required distance from the skin. The errors introduced are obviously greatest for the smaller values of radium-skin distance and applicators at " distance " 10 mm. or less are open to serious objections on these grounds.[11]

For detailed information concerning the mathematical and physical basis of this dosage system the original paper[10] should be consulted. The authors have condensed the more precise physical data into a form which takes account of the fact that discrete radium sources are used in practice. This involves a number of approximations, but they do not affect the accuracy severely except in special instances. Thus, for everyday application of the dosage system, Paterson and Parker have reduced the results to a series of simple rules for the distribution of the radium over surface applicators so that the applicators provide " uniform " irradiation and known surface dosage-rate. The main points of these rules are given in the next section, but anyone contemplating the application of them to their daily practice would be well advised to consult the original work.

4. Distribution Rules for Clinical Application of Paterson and Parker's Dosage System for Surface Applicators

In the following rules[10] the thickness of the applicator, or the distance between the plane carrying the radium and the plane at which the dose is assessed (*i.e.*, the treated area) is referred to as the " distance " (*h*). The relation between the radium used, the area irradiated, the dose at the surface in röntgens and the " distance " is given in the " dosage-graphs " of Figs. 50 and 51. Having

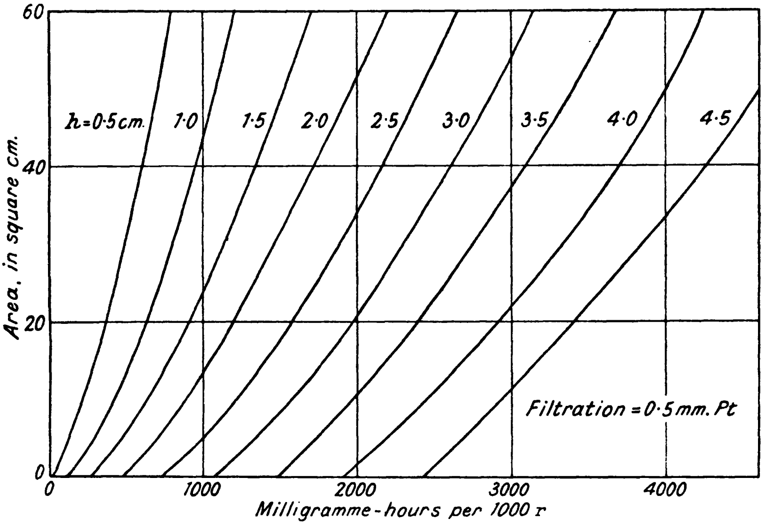

FIG. 50. Dosage graphs for areas up to 60 sq. cm. at " distances " *h* from 0·5 to 4·0 cm. (Paterson and Parker.)

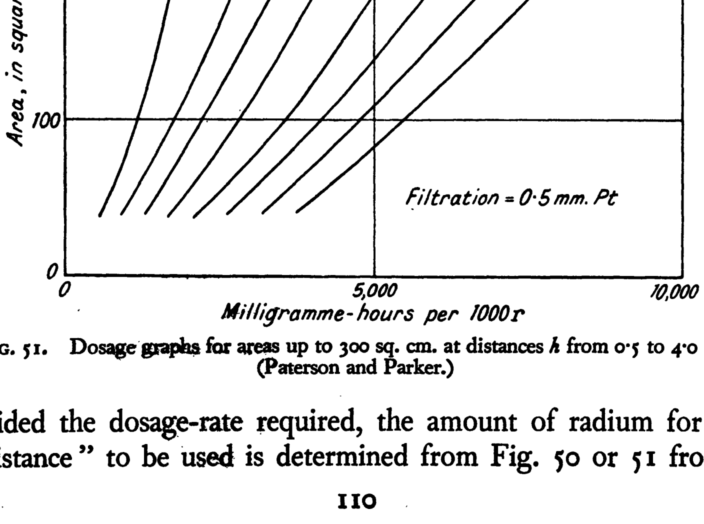

FIG. 51. Dosage graphs for areas up to 300 sq. cm. at distances *h* from 0·5 to 4·0 cm. (Paterson and Parker.)

decided the dosage-rate required, the amount of radium for the " distance " to be used is determined from Fig. 50 or 51 from a knowledge of the area to be treated. This radium is distributed on the applicator in one of the following ways, depending on its shape. In all cases the distance between the active ends of the sources, which are arranged along lines, should not exceed the "distance" h.

Circles. These should be used whenever possible.

Arrange the radium uniformly around the circumference. As many sources as possible should be used, but it is satisfactory if a minimum of six containers is used.

If the diameter of the circle is less than $3h$, a circle alone is sufficient (diameter $= 2{\cdot}83h$ is ideal).

If the diameter is between $3h$ and $6h$, 5 per cent. of the radium is placed at the centre.

For larger areas use two concentric circles and a central spot as follows :—

(i) Put 3 per cent. of total radium at centre.

(ii) The percentage of radium for outer circle as in Table 13, and

(iii) Distribute the remainder around a circle of half diameter.

In addition, Oddie[12] has pointed out that circles up to a diameter of 2·5 cm. can be treated uniformly for $h = 0{\cdot}5$ cm. or 1·0 cm. by means of three needles, each of active length equal to the diameter, placed symmetrically along the sides of an equilateral triangle each of length 4/3 × diameter, so that the ends are open.

TABLE 13.

Outer diameter	$6\,h$	$7{\cdot}5\,h$	$10\,h$
Percentage of radium in outer circle .	80%	75%	70%

Squares. The radium is distributed around the periphery with uniform line density. If gaps exist between the active ends of the sources, they should not exceed h.

If the side of the square is not greater than $2\,h$, no further radium is required.

If the side of the square is greater than $2\,h$, additional lines are added, parallel to one side, to divide the area into widths $= 2\,h$.

For one added line its density = 1/2 that of periphery. For two or more added lines the line density = 2/3 that of periphery.

Rectangles. Proceed as for squares, adding the additional lines parallel to the longer side and increase the milligram-hours for "elongation" in accordance with Table 14.

TABLE 14.—*Corrections to be applied to Dosage Curves for Rectangular Areas* [*Elongation = Ratio of Sides*]

Elongation	2 : 1	3 : 1	4 : 1
Percentage milligram-hours to be added .	5%	9%	12%

Triangles.[12] The radium is distributed uniformly around the periphery together with similar concentric triangles inside, such that the distance between parallel needles = 2 *h*. The inner needles have half the line density of the periphery and the milligram-hours for the "ratio of the triangle's sides" are increased in accordance with Table 15. (See also Appendix IV.)

TABLE 15.—*Corrections to be applied to Dosage Curves for Triangular Areas*

Relative lengths of sides of triangle	Percentage correction	Relative lengths of sides of triangle	Percentage correction
2 : 2 : 3	12	5 : 5 : 4	8
3 : 3 : 4	10	4 : 4 : 3	9
4 : 4 : 5	9	3 : 3 : 2	10
1 : 1 : 1	8	2 : 2 : 1	4

Convex Areas. The rules may be applied to curvatures up to hemispherical or semi-cylindrical curvature. The radium to be used is determined from the graphs for the "area treated," but should be spread over the larger, but corresponding area on the applicator.

Concave Areas. The area measured for dosage purposes is the *area* of *the applicator* regardless of the area treated.

Filtration. Since the dosage graphs are for 0·5 mm. platinum filtration, corrections must be made for other filtrations. These corrections can be deduced from the data given in Chapter II (Table 5).

Depth Dose. The dose delivered by an applicator at a depth *d* may be obtained from the dosage graphs by using the *new* distance ($= h + d$). It must be borne in mind, however, that the dose may not be so homogeneous at these other distances.

Roberts[13] has pointed out the difficulty that often arises in practice, of distributing available radium sources over small applicators exactly in accordance with the rules, and also that for very small areas, the rule of peripheral distribution breaks down. He has made it clear also that with small areas, slight errors in the distance h, as may easily occur in the construction of a mould, lead to greater errors in dosage than if the area is large. He suggests that the difficulties may be overcome by the use of a few standard applicators for routine practice in these cases. For details of these the original work should be consulted.

With regard to experimental tests of the theoretical distribution, Honeyburne and Roberts[14] have made a comparison between the calculated dosage from a circular applicator (ring source) and that found as a result of measurements made in water, the applicator being applied to the surface of the water. They found that at almost all points the dosage-rate in water is lower than that at corresponding points in air and the results suggest that a correction, in the form of a 4 per cent. reduction per centimetre thickness of applicator and tissue, would be sufficiently accurate. They also found that the dosage-rate falls off more rapidly beyond the edge of the applicator than is suggested by theory. This is an advantage clinically, since it means that normal surrounding tissues receive less radiation than might be expected.

5. Some Typical Cases illustrating the Method of Parker and Paterson[10] :

The application of the rules to actual cases may be illustrated as follows :—

These illustrations have been taken from the original paper[10] and are further described in Fig. 52. The examples are deliberately varied in order to illustrate the use of as much of the various data as possible.

(i) *Rodent Ulcer of the Face.* Lesion of inner canthus 1·2 cm. diameter (Fig. 52A).

Treatment by gold seed implantation (non-removable) at 0·5 cm. depth to skin so as to deliver 6,500 *r*.

Calculation: Treat circular area 2·5 cm. diameter $\simeq$ 5 cm^2.

1,000 *r* (at 0·5 cm.) = 155 mgm.-hours, *i.e.*, 6,500 *r* = 1,010 mgm.-hours. 1 initial millicurie = 132·4 mgm.-hours : radon required = $\frac{1{,}010}{132{\cdot}4}$ = 7·6 millicuries. Gold seeds of 0·5 mm. wall thickness do not require a correction for filtration.

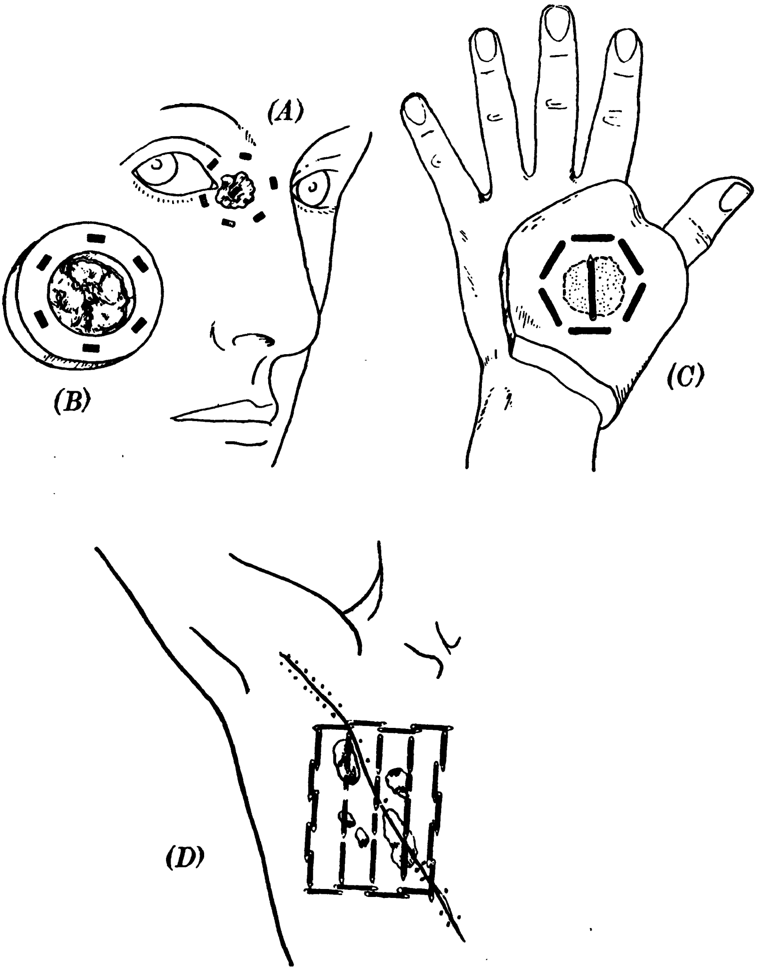

FIG. 52. Typical cases illustrating the distribution of radium on surface applicators in accordance with Paterson and Parker's dosage system. (Paterson and Parker.)

Distribution : Diameter = 5 *h*, hence use a single circle with a 5 per cent. centre spot.

Actually use 6 × 1·1 millicurie seeds plus 1 central weak seed.

(ii) *Nævus of the Face.* Lesion on cheek and 4 cm. diameter (Fig. 52B).

Treated by an elastoplast sorbo applicator, using silver radon seeds to give 1,000 *r* in 5 days.

Calculation: "Ideal" circle 4 cm. diameter is at 1·5 cm. distance. Area = 12·5 cm^2.

1,000 *r* (at 1·5 cm. distance) = 710 mgm.-hours. No filtration correction if 1 mm. silver is used.

1 initial millicurie = 79·1 mgm.-hours in 5 days (see Appendix I).

$$\therefore \text{ Need } \frac{710}{79{\cdot}1} = 9 \text{ millicuries.}$$

Distribution: Use 6, 1·5 millicurie seeds of 1 mm. silver filtration.

(iii) *Epithelioma of Dorsum of Hand.* Lesion 3·5 cm. diameter (Fig. 52C).

Treated by a mould, $h = 1$ cm., to give 6,000 *r* in 20 days, the mould being worn for 16 hours per day.

Calculation: Treat area 5 cm. diameter. Area = 19 cm.^{2} 1,000 *r* (at 1 cm.) = 630 mgm.-hours: 6,000 *r* = 3,780 mgm.-hours. Correction for 1 mm. Pt. filtration: add 10 per cent. so that 4,158 mgm.-hours are needed.

= 13 mgm. for 320 hours.

Distribution: Diameter = 5 *h*. Therefore use a single circle plus 5 per cent. central spot.

Use 6, 2 mgm. tubes in a circle + 1 mgm. tube as centre spot (all 1 mm. Pt.).

Dose at 0·5 cm. below the skin:—

At 1·5 cm. distance, 1,000 *r* = 880 + 88 (10 per cent. for filtration) = 968 mgm.-hours.

Milligram-hours used = 4,158.

$$\text{Depth dose} = \frac{4{,}158}{968} \times 1{,}000\, r = 4{,}300\, r.$$

(iv) *Breast Recurrences in Post-operative Scar.* Over a fairly wide area (Fig. 52D).

Desired to treat an area 8 × 10 cm. with a "one-centimetre" mould to 5,500 *r* in 6 days.

Calculation: Area = 80 cm.^{2}

1,000 *r* (at 1 cm.) = 1,450 mgm.-hours. ∴ 5,500 *r* = 7,975 mgm.-hours.

7,795 mgm.-hours = 56 mgm. for 143 hours. Needles 0·5 mm. Pt. $\therefore$ no filtration correction.

Distribution: Rectangle at 1 cm. + 3 additional lines of $\frac{2}{3}$ line density 2 cm. apart and parallel to 10 cm. side.

1 mgm. per cm. for 36 cm. of periphery and $\frac{2}{3}$ mgm. per cm. for 30 cm. of lines = 56 mgm.

$\therefore$ sides: 5,2 mgm. and 4,2 mgm. respectively.

And lines: 3,2 mgm. and 1,0·66 mgm. respectively.

Dose at 1 cm. below skin :—

At new distance of 2 cm. 1,000 *r* = 2,580 mgm.-hours.

$$\text{Depth dose} = \frac{7{,}975}{2{,}580} \times 1{,}000r = 3{,}100\,r.$$

It is of interest to note the order of magnitude of the dosage-rate used in these cases. For the cases (iii) and (iv) in which needles are used, so that the dosage-rate is constant, it ranges round about 20 to 30 *r*/hr.

6. Cylindrical Surface Applicators

The cylindrical surface applicator is a special type of applicator which has been considered in some detail by Paterson, Parker and Spiers.[15] The mathematical investigation made by these workers followed very similar lines to the work already outlined. It is sufficient here to point out that one of the authors (Spiers) has followed the path of direct calculation, while another (Parker) has arrived at the results by a consideration of the bending of rectangular frameworks such as have been discussed, until a pair of opposite sides coincide, when the applicator takes the form of a series of co-axial rings. It was found that the intensity over a coaxial surface within the radium cylinder, is constant within the limits of ± 10 per cent., provided the distance between adjacent rings does not exceed twice the " distance " (2 *h*). An exception has to be made in the case of the extreme ends of long cylinders. It is thus possible to evaluate a mean intensity over the cylindrical treated surface for each value of $\frac{d}{D}$, where *d* is the diameter of the treated surface and D is the diameter of the radium cylinder.

Applicators of this type occur when a diseased part has to be completely surrounded by an applicator carrying radium as a single ring, or as a cylinder. A single ring is really a cylinder of zero-length. The radium may obviously be in the form of a series of co-axial rings or a series of equidistant lines parallel to the axis of the cylinder. The former method is to be preferred where applicable as it gives a more uniform intensity distribution.

The distribution of radium and the resulting dosage conditions thus worked out for routine clinical practice are as follows :—

Distribution Rules[15]. 1. The radium is placed in a series of co-axial circles at a distance apart equal to 2 *h* (*h* is the "distance" or thickness of the applicator as before).

The total radium is divided between the rings as :—

Two rings . .	$1 : 1$
Three rings . .	$1 : \frac{1}{2} : 1$, *i.e.*, centre ring has half of outer ring.
Four rings . .	$1 : \frac{2}{3} : \frac{2}{3} : 1$
Five rings . .	$1 : \frac{2}{3} : \frac{2}{3} : \frac{2}{3} : 1$, etc.

A ring should be a continuous chain of radium needles or tubes. Provided they are short, however, the needles may be placed at right angles to the plane of the ring in the form of a short belt.

2. *Aliter*. Place radium in a series of straight lines of the necessary length, parallel to the axis of the cylinder and at intervals round the cylinder equal to 2 *h*. Add a ring or short belt of radium at each end. The line density of the radium has to be two-thirds

TABLE 16.—*Milligram-hours to produce* 1,000 *r at the Centre of Rings of different Diameters*[15]

Filtration of Radium = 0·5 *mm. Pt.* 1 I*mc. taken* = 8·4 *r/hr.*

Diameter D in cm.	Mgm. hours	Diameter D in cm.	Mgm. hours	Diameter D in cm.	Mgm. hours	Diameter D in cm.	Mgm. hours
2	119	7	1,460	11	3,600	18	9,640
3	268	7·5	1,670	11·5	3,940	19	10,700
4	476	8	1,900	12	4,290	20	11,900
4·5	603	8·5	2,150	13	5,030	21	13,100
5	744	9	2,410	14	5,830	22	14,400
5·5	900	9·5	2,690	15	6,700	23	15,700
6	1,070	10	2,980	16	7,620	24	17,100
6·5	1,260	10·5	3,280	17	8,600	25	18,600

TABLE 17.—*Factors for Cylinders of Types* 1 *and* 2[15]

$\frac{L}{D}$	$\frac{d}{D}$						
	0·0	0·2	0·4	0·5	0·6	0·7	0·75
0·0	1·00	0·96	0·84	0·75	0·64	0·51	0·44
0·1	1·01	0·98	0·86	0·78	0·68	0·56	0·49
0·2	1·06	1·02	0·92	0·84	0·75	0·64	0·57
0·3	1·12	1·09	1·00	0·93	0·83	0·73	0·64
0·4	1·18	1·15	1·07	1·00	0·90	0·80	0·74
0·5	1·24	1·21	1·13	1·07	0·97	0·87	0·82
0·6	1·31	1·28	1·20	1·12	1·04	0·94	0·88
0·8	1·45	1·41	1·34	1·28	1·18	1·08	1·01
1·0	1·60	1·56	1·49	1·43	1·33	1·21	1·14
1·2	1·73	1·69	1·62	1·55	1·45	1·33	1·26
1·4	1·86	1·83	1·74	1·68	1·58	1·46	1·39
1·6	2·00	1·96	1·87	1·80	1·69	1·57	1·49
1·8	2·15	2·11	2·02	1·94	1·83	1·69	1·61
2·0	2·31	2·27	2·18	2·09	1·97	1·82	1·74

of that in the end rings. This method should be used only when needles suitable for the first method are not available.

Dosage: When the radium is distributed in accordance with these rules, the dosage may be determined by reference to the data set out in Tables 16 and 17, which are taken from the original paper.[15]

Table 16 gives the number of milligram-hours to produce 1,000 *r* at the centre of a ring of any chosen diameter when the radium is filtered by 0·5 mm. Pt. The values for heavier filtrations may be obtained by increasing these values in accordance with the data of Chapter II (Table 5). These values were obtained by direct calculation. The milligram-hours required to produce 1,000 *r* at any given surface inside a radium cylinder (*e.g.*, the skin surface of the treated part), may be derived from the basis figure for a ring of the same diameter, obtained from Table 16, which is multiplied by the appropriate factor from Table 17. This factor is determined by the ratio $\frac{L}{D}$ (L is the length and D the diameter of the radium cylinder) and by the ratio $\frac{d}{D}$ (*d* is the diameter of the surface concerned).

Incomplete rings or cylinders are sometimes, but not frequently, required, and reference should be made to the original work[15] for the modifications necessary for such cases.

Epithelioma of the glans penis lends itself admirably to treatment with a cylindrical applicator, and the following illustration of such a case[15] serves to demonstrate the procedure employed in the application of the rules :—

Penile shaft, average diameter 3 cm. to be treated over a length of 9 cm. at a distance of 1·5 cm. Dose required is 7,000 *r* in 21 days.

$$d = 3 \text{ cm.} \quad D = 6 \text{ cm.} \quad L = 9 \text{ cm.} \quad \frac{L}{D} = 1{\cdot}5\,; \ \frac{d}{D} = 0{\cdot}5.$$

From Table 16, for D = 6 cm., 1,000 *r* = 1,070 mgm.-hours for 0·5 mm. Pt. filtration.

From Table 17, for $\frac{L}{D} = 1{\cdot}5$ and $\frac{d}{D} = 0{\cdot}5$ the factor is 1·74.

∴ At treated surface, 1,000 *r* is given by 1·74 × 1,070 = 1,860 mgm.-hours.

∴ 7,000 *r* is given by 13,000 mgm.-hours.

Time, 16 hours per diem for 21 days, ∴ Radium required = 38·7 mgm.

Along the cylinder axis (*i.e.*, at urethra) $d = 0$ and the factor is 1·93.

$$\therefore \text{Dose} = \frac{1{\cdot}74}{1{\cdot}93} \times 7{,}000\,r = 6{,}320\,r \text{ (90 per cent.)}.$$

Distribution : Using the second rule, the circumference of the cylinder is 19 cm. and 2 *h* is 3 cm. Use 6 lines parallel to the axis with a ring at each end. Then if ρ mgm./cm. is the line density in the end rings :—

$$\underset{\text{(end rings)}}{2 \times 19 \times \rho} + \underset{\text{(six lines)}}{6 \times 9 \times \tfrac{2}{3}\rho} = 38{\cdot}7 \quad \text{Whence } \rho = 0{\cdot}52 \text{ mgm./cm.}$$

Thus, approximately 10 mgm. is needed in each end ring and 3 mgm. in each line, total 38 mgm. This is illustrated in Fig. 53.

Further details of this method of treatment and of the distribution of the radium in rings according to the first rule has been given by Hutchison.[16]

The methods outlined above are being applied more and more

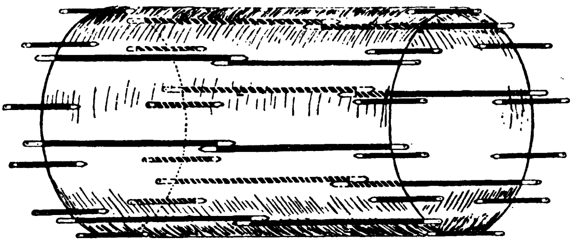

FIG. 53. Arrangement of needles on a cylindrical applicator. (Paterson, Parker and Spears.)

in institutes and clinics where radium surface irradiation is used to any extent, and this use is leading to more and more precise information and to greater control of the physical factors in this kind of treatment.

7. "Cosine" Radiating Surfaces

An exceedingly interesting and original contribution to the study of surface applicators has been made by Van Roojen.[17,18] The method he has put forward has much to recommend it and it is possible that the future may see it applied to some extent, but, as will be seen, its requirements tend to hamper its speedy adoption.

Van Roojen considered a hypothetical gamma ray emitting surface whose gamma ray emission obeys the law of heat radiation in that it is proportional to the cosine of the angle between the direction of emission and the normal to the surface. Such a surface has a number of special characteristics. In a closed envelope there is a constant intensity and the intensity is finite on the surface itself. (With normal radium sources the intensity tends to extremely high values as one approaches the source). For small fields applied to a scattering and absorbing medium comparable with tissue, absorption is negligible, but it is not inappreciable for large fields. The general problem of the field produced by any such "cosine" surface is identical with that of the magnetic potential produced by a magnetic sheet or by an electric current round the boundary of the surface. Thus the intensity I_p at any point P due to such a surface may be written :—

$$I_p = k\int d\omega \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where k is a suitable constant depending upon the radium density and $\int d\omega$ is the total solid angle subtended at P by the surface.

The method thus depends upon a determination of the solid angles subtended in specific cases.

Van Roojen has shown that about one-third more radium is required to produce a " cosine " surface than an ordinary surface, but the " cosine " surface gives better depth doses than are obtained by ordinary methods. Such surfaces could be applied directly to the affected part and for any given purpose, the time of application would be the same for small and large discs.

Further, it was shown that a " cosine " surface might be approximately realised by making a " radium alloy " of radium and some metal of high atomic weight such as platinum, gold, lead or bismuth. In some experiments bismuth was actually used.[18] The thickness of such an alloy that is required is not unduly great and only of the order of a few millimetres. For practical use Van Roojen visualises small, square pieces of radium alloy from which larger surfaces may be built up as required and moulded directly to the surfaces to be treated.

It is seen that such a method would have much to recommend it from the point of view of extreme simplicity of application if the alloy was available. Its main disadvantages are economic. At the present time the available medical stocks of radium are in the form of needles and small plaques, and so would need much modification. Once they were modified some of the flexibility of use permitted by needles would be lost. However, if economy does permit, the method is definitely worthy of trial.

8. The Construction of Surface Applicators

The materials used for the construction of surface applicators should be light in weight so that the assumed radiation distributions will not be interfered with seriously. In the past quite a number of substances have been so employed.*

Columbia Paste,[20] a mixture of beeswax, paraffin wax and fine white wood sawdust, in the proportions 10 : 10 : 2, has been widely used and is eminently suitable where small areas are involved and little fine moulding is required. It may be prepared in sheets of any desired thickness according to the " distance " required.

At Westminster Hospital,[21] where surface applicators have been chiefly used for the irradiation of fairly wide areas at the comparatively large " distance " of 4 cm., sheet sorbo-rubber has been used. This may be obtained in thicknesses from 0·5 to 2 cm. The pliability of this material enables one to ensure accurate fitting to the patient without intermediate plaster casts. In order to obtain the required 4 cm. distance, light wooden boxes are attached to the sorbo-rubber foundation by means of adhesive plaster. The radium is carried in these boxes. This method of mounting the radium needles sometimes makes it difficult to conform to the correct distribution rules as accurately as one would wish, but in the use of large areas at this radium-skin distance, any slight errors of this nature are not so serious as in the case of small applicators using small " distances." A typical applicator of this kind is shown in Fig. 54.

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* Also see D. G. Walker.[19]

In order that methods might be evolved to allow the accurate use of the distribution rules which they have worked out as we have described, the workers of the Holt Radium Institute, Manchester, have devoted much time and thought to the construction of surface applicators. A detailed and very valuable account of the constructional methods that have thus been evolved has been given by Paterson and MacVicar.[22] A careful consideration of the combined use of the distribution rules and these precise methods of applicator construction, leads one to appreciate both the number, and variety of cases, that can be treated by superficial and buccal applicators with real accuracy and effectiveness. We shall give below some of the main points made by Paterson and MacVicar,[22] but any who wish to apply their methods thoroughly should consult the original work.

If the method of surface application is to be applied successfully, the following conditions must be fulfilled :—

(*a*) The " treated " area (to be uniformly irradiated) should extend well wide of the obvious tumour area.

(*b*) Applicators must be such as to allow accurate placing of the radium in relation to each individual lesion, and the accurate maintenance of the radium-skin distance, especially for small distance.

(*c*) Applicators must fit accurately so that they are easy to place in position and remain strictly in position.

To meet these conditions Paterson and MacVicar hold the opinion very strongly that a separate applicator must be made for

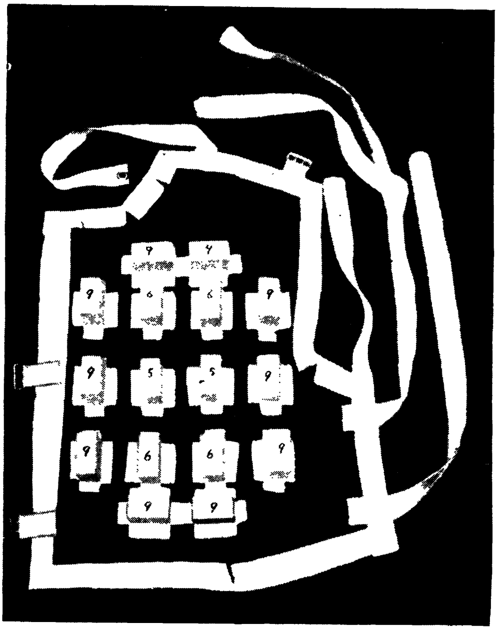

FIG. 54. Typical large breast applicator as used at Westminster Hospital. (Cade.)

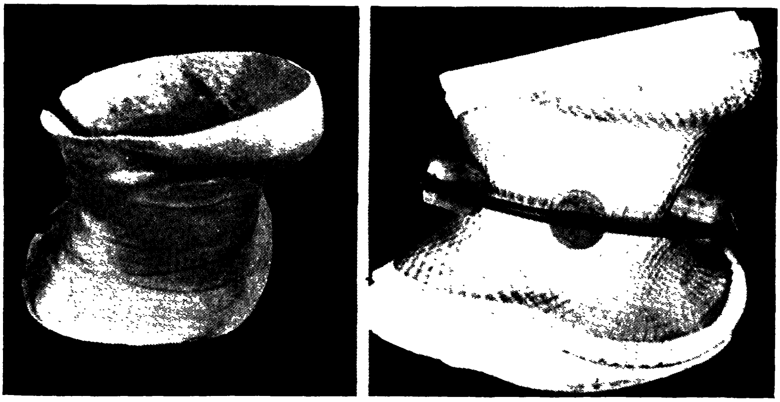

FIG. 55. Steps in the construction of a radium collar (Paterson and McVicar.)
(*a*) Impression of the whole neck is made by a plaster bandage.
(*b*) Radium is mounted on Nidrose applicator moulded to the impression.

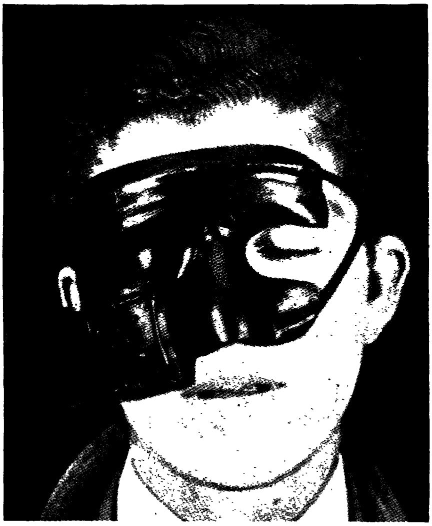

FIG. 56. Naso-malar applicator in "black tray" compound, before the radium is sealed in. (Paterson and McVicar.)

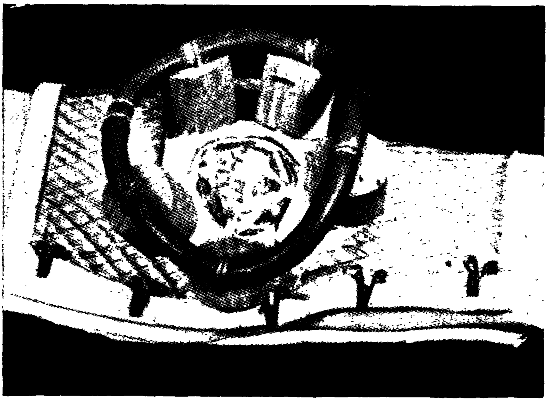

FIG. 57. A Nidrose Applicator fastened to a limb. The radium is carried within the rubber tube. (Paterson and McVicar.)

each patient. In general (with a few exceptions), there are three stages in the construction of every applicator :—

(i) The taking of an " impression " of the lesion and surrounding parts.

(ii) The construction of the " model " or cast in plaster of Paris, from the impression.

(iii) The construction of the actual " applicator " on the model or, exceptionally, directly on the patient.

The materials found to be satisfactory are listed in Table 18 on p. 124 with short notes concerning their source of supply and use. In this table reference is made also to applicators that are prepared for use within the mouth. These will be referred to again in the next chapter when intra-oral irradiation is discussed.

Typical methods of carrying out the construction of surface applicators in accordance with the above processes are illustrated in Figs. 55, 56 and 57, which are taken from Paterson and MacVicar's original paper.[22] Fig. 55 shows the method of taking an impression of the whole neck by means of plaster bandage and the method of mounting a " radium-collar " on the Nidrose applicator moulded upon the model so obtained. Fig. 56 shows a Naso-malar applicator with the radium mounted in " Black Tray " compound, before it is sealed in. Fig. 57 illustrates a Nidrose applicator fastened on the limb by means of a lace fastening; the radium is mounted on corks within a rubber tube. Paterson and MacVicar point out that although many of the operations of construction require some practice for the best results, all the applicators used by them are manufactured by lay technicians.

A question that sometimes arises in radium therapy with surface applicators is that of the protection of healthy tissues from radiation. The introduction of say lead, as a screen for the gamma rays, may introduce an excess of harmful secondary beta radiation, and the question is one of proportion. Roberts [23] examined this matter in a series of experiments and concluded that " for most purposes lead is the most satisfactory material, its high gamma ray absorption coefficient more than compensating for its comparatively large secondary beta ray emission. A thin layer of copper over the lead filtration appreciably reduces the surface ionization, but this may have little or no effect on the skin reactions because of the low penetrating power of the secondary beta rays."

TABLE 18.—*Materials used in the construction of Surface applicators. (Paterson and MacVicar*[22]*)*

Purpose of material	Material	Notes and remarks concerning material
For taking impressions of surface lesions.	Crown impression compound.	Supplied by Amalgamated Dental Co. Cost is low. Plastic after few minutes in hot water. Remains malleable to permit accurate moulding.
	Plaster of Paris bandage.	Suitable for neck or limbs. Cellona plaster used. Fast setting obtained by moistening in hot salt water. Vaseline prevents sticking on hairy parts.
	Dentacol.	Supplied by Amalgamated Dental Co. for very accurate impressions in tender places. More difficult to use.
For impressions of the mouth.	Dentacol.	*Ibid.*
	Elasto-Velvex.	Supplied by Ash & Co. Pliable for some time after heating in water at 60° C.
For models of surface lesions.	Plaster of Paris.	Ordinary crude plaster of Paris is sufficiently good for large models such as head, neck, face, etc.
For models of mouth lesions.	Calspar.	A special plaster of Paris supplied by Ash & Co. Quick-setting. Of extremely fine texture. Almost no expansion on drying.
For surface applicators.	Base plate + "Black Tray" compound.	Base plate of two types, Alston's and Attenborough's. Both supplied by Ash & Co. (See also below.) Black Tray compound supplied by Ash & Co. (See also below.)
	Nidrose.	Supplied by Beuneau & Cie, Paris. Expensive. When heated can be moulded to plaster model. Light in weight and cool for wear over long periods.
	Elastoplast and Elastoplast felt.	Of value in small, flat, superficial lesions such as nævi, rodent ulcers, etc. Used with radon seeds, these make excellent out-patient moulds.
For mouth applicators.	Base plate.	
	"Black Tray" compound.	

9. Measurement of the Dosage from Surface Applicators

An excellent account of the measurement of radium surface applicators or plaques has been given by L. H. Gray (Reference 21, Chap. V). When the radium upon an applicator has been distributed according to the distribution rules worked out for homogeneous irradiation, the number of measurements required in order to check the final result will be reduced to a minimum. The results of the measurements add to the accuracy of the dosage in that they take into account the small divergences from theory resulting from the affects of scatter, absorption, oblique filtration, etc., which cannot be allowed for theoretically.

For the actual measurements, any of the instruments described in Chapter IV may be used provided that the size of ionization chamber and sensitivity of the measuring system are suitable for the particular applicator concerned. It is usually simplest to calibrate the instrument in terms of dosage-rate (*r*/min. or *r*/hr.) by means of a standard source used at accurately known distances from the ionization chamber.

In order to investigate the radiation from a surface applicator adequately by direct measurement, some form of movable system, capable of providing accurately known movements in at least two, or preferably three dimensions, is required. If a large, fixed type of apparatus is used, the applicator is made the movable part of the system, but if the condenser chamber technique is resorted to, it is quite convenient to move the ionization chamber. The dosage-rate is measured for a number of representative points on the surface of the applicator, over a range of distances from the surface, the smallest of which will be determined by the size of the ionization chamber (*i.e.*, when the chamber is in contact with the surface of the applicator). For each surface point considered, a graph may be drawn showing how the dosage-rate changes with distance from the surface; the actual surface dosage-rate at the point in question may be obtained by extrapolating the curve back to the surface. The dosage-rate at the lesion may also be interpolated if the depth of the lesion is given.

As an example of the kind of results obtained, Table 19 is a summary of the surface dosage-rates measured by means of elektron metal condenser chambers at eleven different points beneath a 12 × 12 cm. applicator. The radium was mounted on the applicator as closely in accordance with the Paterson and Parker distribution rules as the method used at Westminster Hospital (in boxes) allowed. The theoretical dosage-rate was 7·3 *r*/hr., agreeing

TABLE 19.—*Values of Surface Dosage-rate measured over a 12 × 12 cm. Applicator; 48 mgm. Radium Element* (0·5 *mm. Pt.*) *at* 4·0 *cm. Distance*

Point on surface	1	2	3	4	5	6	7	8	9	10	11
Surface dosage-rate in r/hr.	6·88	7·08	6·83	6·72	7·68	6·72	7·33	7·35	6·74	7·36	6·65

Mean dosage-rate = 7·02 r/hr. (± 4 per cent.).

very closely with the mean of the measured values, all of which show only a small variation between themselves. These measurements were made with a back scattering medium of paraffin wax. For measurements made solely in air, Gray (Reference 21, p. 96) has given tables for radium-skin distances of 3 cm. and 5 cm., which state the corrections to be added or subtracted to allow for back-scatter and absorption in surface and depth measurements. The values for 4 cm. " distance " can be interpolated from these tables.

A large number of measurements on surface applicators, loaded in accordance with the Paterson and Parker methods, which have been made by Cook,[24] led him to draw up tables enabling one to correct for the absorption of radiation in the material of the applicator and for tissue back-scatter. These corrections are useful when treatments are given solely on the basis of an " air-calculated " dosage-rate, such as is provided by the data of Paterson and Parker. In general, however, if facilities and time permit, a direct measurement of dosage-rate is to be preferred in all circumstances.

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CHAPTER VI

CAVITARY AND INTERSTITIAL RADIUM THERAPY

It is probably true that from the viewpoint of the physical aspects, the methods of radium treatment whereby the sources are introduced into natural or artificial cavities (cavitary method), or inserted into the tissues themselves (interstitial method), have been studied less than the other methods used to-day. Within recent years, however, a considerable body of physical information concerning these methods has been forthcoming, and this has led to distinct improvements in techniques and their specification. With the passage of time it is likely that the tendency will be to replace many of these methods by distance irradiation, but at present, especially from the economic standpoint, they have a very definite place in radiation therapy. It must be said, however, that in the general use of these methods, planning of treatment, with regard to homogeneity of dosage, value of dosage, etc., is not so generally prevalent as in surface or distance irradiation methods. In this connection perhaps, it is not sufficiently well realised how much, within the limits prescribed by the patient's anatomy, the physicist may assist the surgeon in his work.

In the preparation of the brief descriptions given below, of the clinical procedure used in the application of cavitary and interstitial methods of radium therapy, considerable reference has been made to Mr. Stanford Cade's book "Malignant Disease and its Treatment by Radium." For further information concerning these methods, reference should be made to this volume, where admirable detailed accounts are given.[1]

1. Cavitary Methods

In the cavitary method of radium therapy the radiation foci (tubes, needles or radon seeds) are introduced through natural or artificial openings into the cavities of hollow organs. "The method is used commonly in the uterus, the maxillary antrum and nasal sinuses, occasionally in the rectum, the large bronchii and œsophagus; exceptionally in the treatment of buccal lesions, the palate and the vagina."[1] The radium used is usually highly filtered because the radium is placed in close contact with the tissues, although it is likely that the extra distance involved is of greater value than the added filtration. Thus in the uterus and dome of the vagina 1·5–2 mm. of platinum filtration is used, and in the nose 0·8–1·0 mm. platinum. In addition a secondary filter is added to keep secondary beta radiation to a minimum. This may be 2 or 3 mm. thickness of a light material such as rubber or vulcanite or a sufficient thickness of a medium atomic number material such as silver.

From the physical standpoint, in common with other methods of irradiation, any technique that may be proposed in the use of the cavitary method should be such as to provide for the greatest possible homogeneity of dosage throughout the tissues it is desired to irradiate, compatible of course, with any other conditions that must be fulfilled. In general, with the information now available, it is possible to decide upon the most suitable disposition of the radium to this end. We shall discuss some of the various cavitary methods in order to indicate the available information concerning the dosage and its homogeneity and to illustrate how physical principles may be employed to appreciably improve the conditions of irradiation.

2. Radium Treatment of Carcinoma of the Cervix

The question of radium treatment of carcinoma of the cervix is one that has received a great deal of attention, especially in recent years, when the dosage conditions pertaining to the various techniques have been widely discussed.

(*a*) TECHNIQUES OF TREATMENT. (i) *The Paris Method of Regaud.*[2] A total quantity of 66·6 mgm. of radium is used, one-half being inserted into the uterine cavity and the other half into the vagina. The uterine tubes have 1 mm. platinum filtration and are further contained in a hollow gum-elastic tube 6 cm. long and 1·5 mm. wall thickness. Those tubes placed in the vagina have 1·5 mm. platinum filtration and are held in the centre of cylindrical corks 2 cm. in diameter. Two cork containers are joined together by a metal spring, so forming a carrier known as the colpostat. A cork is placed in each of the lateral fornices and, if needed, a third container is placed against the central part of the lesion or against the cervix. The dispositions of the sources during treatment are illustrated in Fig. 58, which is a radiograph[3] showing the position of the vaginal applicators relative to the pelvis.

The gum-elastic tube and corks surrounding the radium tubes serve to minimise secondary beta radiation, but what is more important, they serve to increase the distance between the radium and the tissues nearest the latter. This distance increases the dose received at a depth relative to that received by the nearest tissues.

Small variations in the radium quantities are sometimes used, but the technique is characterised by the fact that the irradiation is continuous, the radium being left *in situ* for several days.

(ii) *The Stockholm Method of Heyman.*[4] In this method the treatment is given fractionally; usually three treatments of twenty hours' duration spread over a total period of one month. The radium quantity is greater than in the Paris method, usually a 40–50 mgm. tube in the uterine cavity and 60–75 mgm. in the dome of the vagina. The actual technique varies according to the extent and shape of the tumour so that a number of different applicators are used. "The selection of the applicator has two objects in view. One is to cover as far as possible the entire original surface of the tumour, the other to distend the vagina laterally so that the radium comes as close as possible to the lateral pelvic walls."[4] Minor modifications of this technique are employed at various centres, the modification mainly being in the detail of radium arrangements.

Thus at the Marie Curie Hospital, London, the intra-uterine tube contains 50 mgm. of radium in two tubes of 25 mgm., each having total screenage of 1·0 mm. platinum and 1·5 mm. rubber. The vaginal applicators are three silver, box-like applicators containing five tubes of 5 mgm. each, with effective filtration of 1·2 mm. platinum, which are placed well out into the fornices to ensure a wide cone of radiation.[1]

At Mount Vernon Hospital the intra-uterine tube contains 50 mgm. of radium screened by 1·5 mm. platinum and 1 mm. rubber and is slightly cranked, while the vaginal radium consists of 62·5 mgm. of radium; five tubes in each of two silver boxes. These boxes are attached to the Donaldson butterfly pessary.[5] A screw in the stem of the pessary enables the boxes to be separated as desired after they have been introduced into the vagina in close apposition. Fig. 59 is a radiograph showing the radium in position in this technique.

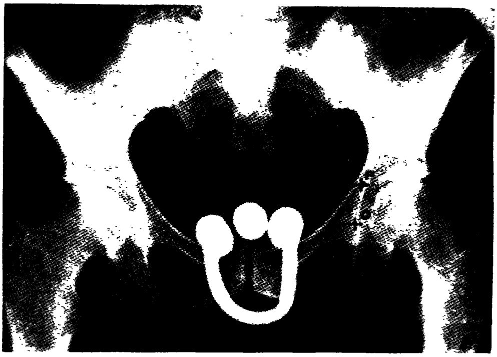

FIG. 58.—Radiograph showing disposition of radium (colpostat) in the Paris technique. (Taylor.)

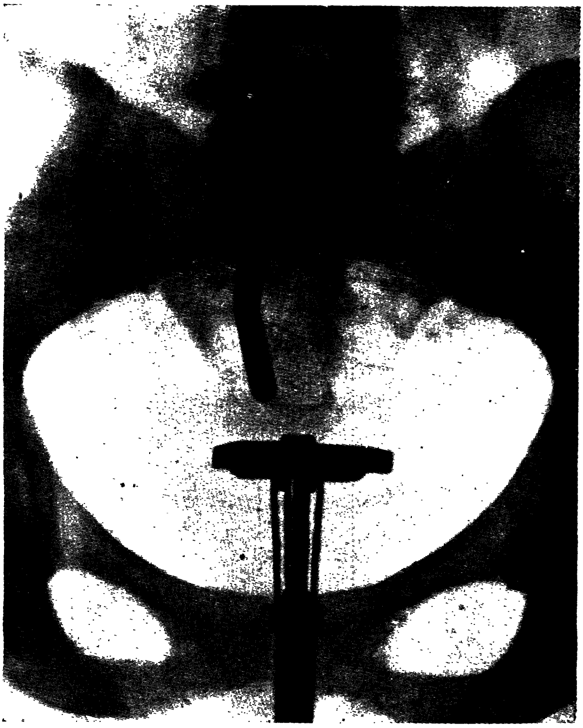

FIG. 59.—Radiograph showing intra-uterine radium tube and Donaldson pessary carrying two vaginal boxes containing radium. (Cade.)

(iii) *The Manchester Method.*[6] Following the progressive lines that one has come to associate with the Holt Radium Institute, Manchester, Tod and Meredith,[6] at this Institute, have shown that it is possible, by arranging the radium in specially designed intracavitary applicators, to fix the relationship of the radium to certain important points within the pelvis so that the dose at these points can be pre-calculated. The vaginal radium is carried in rubber " ovoids " whose shape follows that of the isodose surface around the radium source contained within. The latter is 1·5 cm. long, and may contain 3, 4 or 5 " units " of radium according to whether the ovoid is small, medium or large. Similarly the intra-uterine tube may be short, medium or long and contain 2 " units," 2 and 1 " unit " or 2, 2 and 1 " units " of radium according to the length of the uterus. Thus by combinations of these radioactive foci, which depend upon the known dimensions of the vagina, etc., known dosage conditions may be set up.

(*b*) DISTRIBUTION OF RADIATION AND DOSAGE. A number of investigations have been made concerning the questions of dosage and distribution of radiation in the various techniques described. These have been by direct measurements of the radiation, usually in a model or its equivalent or, more frequently, by means of calculation.

D'Abreu and Banks [7] made a survey, by means of direct measurement within a model pelvis, of the radiation fields in the pelvis for the techniques used at St. Bartholomew's Hospital and Mount Vernon Hospital. Their results showed that the techniques studied give very similar distributions, but in no case was a uniform field obtained. The dosage-rates recorded varied between 10 and 150 *r*/hr., according to the site of measurement.

Langmead [8] studied the dosage possibilities for the Donaldson butterfly pessary combined with a 50 mgm. intra-uterine tube by measuring in air, the distribution of radiation around the tube and separate wings of the pessary. The resultant distribution depends upon how far the wings are opened. For the arrangement shown in the radiograph of Fig. 59, the total distribution of radiation in a vertical plane through the mid-line is that of Fig. 60. The point A is near the centre of the primary growth in the cervix and the point B is in the region of the obturator gland. The dosage-rate at A was found to vary between 92 *r*/hr. and 120 *r*/hr., depending

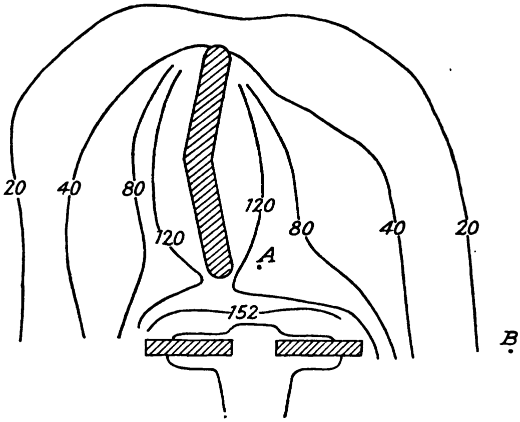

FIG. 60.—Dose contours for radium distribution of Fig. 59, expressed in röntgens per hour.

upon the position of the butterfly wings, but at B, where the value was only 16 *r*/hr., the position of the wings has little effect. Thus for three treatments of twenty-four hours each,[1] the total dose at the cervix and immediate para-cervical area is between 6,600 *r* and 8,600 *r*, while in the region of the obturator gland it is only of the order of 1,150 *r*.

In a very recent paper Neary[9] has made a detailed physical investigation of this same technique, studying the doses received at the rectum and bladder in addition to the points A and B. The following essential points are taken from his summary :—

1. The dose in the parametrium is 6,750 *r*, while the dose in the first principal lymph node near the lateral pelvic wall is 1,900 *r*.
2. Direct measurements with a condenser dosemeter in the rectum of the patient indicate a dose at the anterior rectal wall of about 3,000 *r*.
3. There is no evidence that the vaginal vault receives higher doses with boxes than with corks, etc. Very little of the mucosal area receives more than about 14,000 *r*.

Similar conclusions have been reached by Taylor[3] as a result of calculations of the dosage distribution for the Paris technique.

Sandler[10] has studied, by means of mathematical calculation, the dosage delivered at various points distributed throughout the pelvis by the techniques used at the Marie Curie, Paris and Manchester clinics, and has pointed out the fundamental importance of the size of the vagina in determining the dose. Variations of 1,000–2,000 *r* in the total dose to the pelvic wall were found for the same technique in different sizes of vagina. In addition it was pointed out that the local growth often receives more than what is recognised as a cancericidal dose so that this, combined with a considerable X-ray dose concentrated on the cervix, as occurs in many techniques, "is not only redundant but dangerous." On the other hand, Sandler found that the dose delivered to the pelvic lymph nodes is quite often very small, and it can be said on empirical grounds that this dose "falls far short of an effective lethal dose to carcinoma in this region." This fits in with the dosage values given by Tod and Meredith[6] for the Manchester technique. They showed that this delivers "7,200 *r* throughout the selected zone of paracervical tissue in ten days, but the dose delivered to the region of the obturator gland is only in the region of 2,400 *r*."

In a further more recent paper Sandler[11] has given still more consideration to the radium distribution factor in treatment of carcinoma of the cervix. He has shown that the depth dose is affected much more by the size of the vagina in certain cases than by the type of technique used in it. Large ovoid applicators prove to give a better depth dose than box-like applicators. Sandler insists that each size of vagina should have its own technique specially designed to take full advantage of the vaginal dimensions, and he suggests the use of a rigid, sectional applicator capable of delivering exactly, any given dose prescribed, which can be correlated with the X-ray technique.

All the investigations show that while the dose received by the immediate disease is adequate (in the light of our knowledge to date[12]) for all the various techniques, the dose received by tissues near the pelvic wall is usually far below the minimum dose required to destroy active malignant cells. Because of this, supplementary X-ray treatment is given by one or other methods[1] such that the lateral pelvic wall and the parametria are adequately irradiated without any increase in the radiation received by the central regions of the pelvis.

From the physical point of view, further progress will no doubt occur from a more detailed study of the three-dimensional radiation distributions throughout the whole pelvis for the total, combined (gamma ray plus X-ray) technique. This information, combined with some such method as suggested above by Sandler, should make the treatment of carcinoma of the cervix even more precise and more capable of pre-determination.

The beginnings of this progress has appeared already in recent literature. Thus Neary[13] has made an excellent mathematical analysis of arrangements of radium used in the vagina and uterus. One of his very important conclusions, among others, is that the optimum arrangement consists normally of a single vaginal applicator without a uterine applicator of the usual type. Mayneord and Honeyburne[14] have made a three-dimensional study of the gamma ray distribution in the pelvis in the Marie Curie Hospital technique, and Sandler[15] has described some preliminary investigations into the planning of combined radiotherapy (radium and X-ray therapy) of carcinoma of the cervix, particularly from the point of view of the three-dimensional distribution of total radiation.

3. General Problems of Cavitary Irradiation

We may indicate the kind of physical approach that should be made to the problems of cavitary irradiation in order to approximate to desirable conditions of homogeneity, etc., by reference to some specific types of this form of radium therapy. To achieve the optimum physical conditions is frequently a difficult matter, but often, much could be done that is left undone, by means of closer collaboration between the surgeon and the physicist. The guiding principles in arranging the radium to approach the desired conditions most closely are, (*a*) to arrange the radioactive foci so as to obtain maximum possible homogeneity of radiation at the diseased tissues and (*b*) to arrange that the distance between the foci and the diseased tissues is such that the maximum possible depth dose is obtained compatible with the anatomical conditions and required dosage-rate. In the arrangement of sources it is wise, whenever possible, to utilise the methods of Paterson and Parker[16] (Chap. V). It should be noted that once more, the principle advocated is that the radium should be pre-arranged to give certain definite dosage conditions in contra-distinction to using some arrangement of radium which is investigated after treatment, if at all.

(*a*) IRRADIATION FOR CANCER OF THE MAXILLARY ANTRUM AND ETHMOID.[1] In this method the antrum is fenestrated (the surgical technique has been described in detail by Cade[1]) for complete or partial removal of the diseased tissues and the cavity remaining is used to accommodate a suitable radium applicator. Some days after operation a hollow model of the cavity is made from a plaster cast which consists of two separate shellac applicators fitting accurately one into the other (General Ref. 1). About 10–50 mgm. of radium is usually distributed on the outer surface of the inner applicator and is made up of a number of small, low content needles. A large number of needles permits a more uniform distribution, and small needles are better accommodated to the severe curves of the applicator that are frequently involved. With the needles in position the outer applicator is put over the inner and the edges sealed. The applicator is worn for a number of hours daily until a satisfactory clinical reaction is obtained.

Measurements made of the "contact dose" at a number of points over the surface of such applicators[1] show that the dosage-rate suffers very extreme variations; in one case ranging from a minimum value of 11·5 *r*/hr. up to a maximum value of 79 *r*/hr., a variation that is far from homogeneity. Such large variations arise partly because even the smallest needles available do not allow of a good distribution, but mainly because the radium is so very close to the surface being irradiated that these variations are almost inevitable. Further, because of this small distance between the radium and the nearest tissue, the dose falls extremely rapidly with depth in the tissue.

The author has suggested some modifications in the mounting and distribution of the radioactive foci which lead to a distinct improvement in the distribution of radiation. Firstly, in order that a larger number of small-sized sources may be used, it has been suggested that radon seeds (only 5 mm. long as compared with 9 mm. for the shortest needles) be used and, in order that the dosage-rate be maintained at a high level, that the apparatus be recharged every three to four days. Some workers of course, might not consider such a recharge to be necessary. In addition, we have arranged to introduce an effective "distance" of at least 5 mm. For this purpose a mould of soft plasticine is carried within the cavity of the shellac applicator. The radon seeds are carried within this mould, being introduced to a known depth and distributed as closely in accordance with the Paterson and Parker[16] rules for surface applicators as the shape of the applicator will allow. In practice, if recharging is to be used, a number of plasticine moulds may be taken at one time, so that the new charge may be prepared while the applicator is in use. If the inner surface of the shellac is generously smeared with glycerine the plasticine does not adhere to it.

Fig. 61 (facing p. 139) illustrates a typical applicator of this type and Table 20 gives the results of a number of direct measurements of dosage-rate, made at four widely separated points over its surface, when the radon charge was made in the manner described. It is seen how relatively uniform is the radiation distribution, and furthermore, in view of the fact that 5 mm. "distance" is now used an improved depth dose is obtained.

TABLE 20.—*Measured Dosage-rate on Surface of Antrum Applicator*

44·5 millicuries of radon in 14 seeds of suitable strengths; "distance" = 5 mm.

Site No.	1	2	3	4
Dosage-rate, *r*/hr.	139	164	181	198

(*b*) CAVITARY IRRADIATION OF THE RECTUM.[1] In the cavitary irradiation of carcinoma of the rectum, the most common pro-

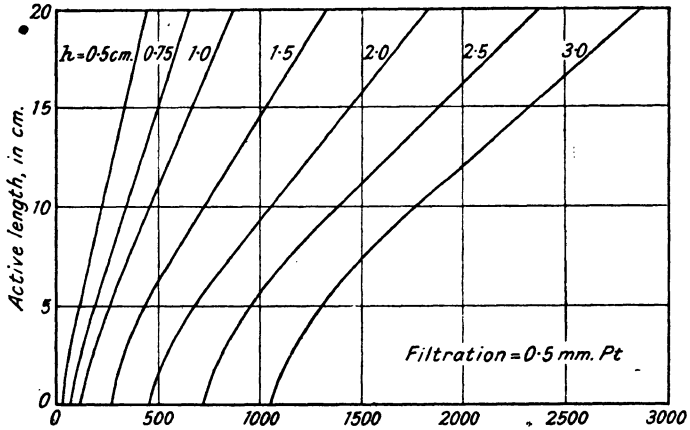

FIG. 62.—Dosage at the surface of tubal applicators of lengths up to 20 cm. and for radii (*h*) from 0·5 to 3·0 cm. (0·5 mm. platinum filter). (*Paterson and Parker.*)

cedure, especially for encircling growths, is to use tubular (linear) radium sources of one form or another. When this method is used the dosage may be assessed by reference to dosage charts drawn up by Paterson and Parker[16] which are reproduced in Figs. 62 and 63. The charts give the dosage in milligram-hours

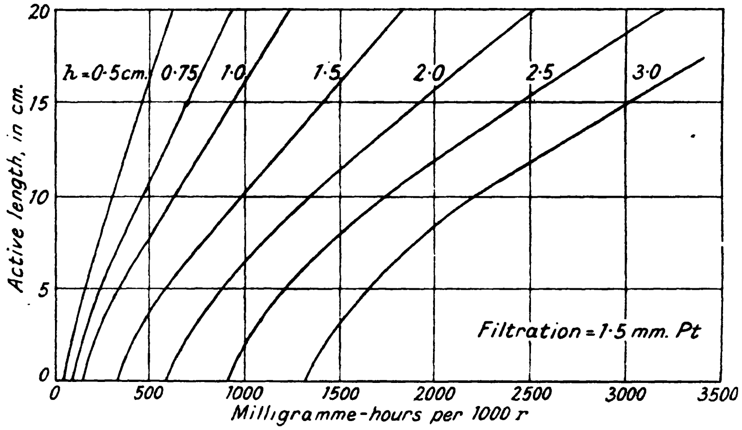

FIG. 63.—As Fig. 62 but for 1·5 mm. platinum filtration. (*Paterson and Parker.*)

per 1,000 *r* expressed in terms of the active length of the rectilinear source. Curves are given for various values of *h*, the distance between the actual radium and the surface of the lesion. Fig. 62 is for 0·5 mm. platinum filtration and Fig. 63 for 1·5 mm. The values for 1·0 mm. platinum are exactly the means of the values for these filtrations. From the same curves the value of the depth dose at any depth may be determined. Thus, the dosage at a depth *d* is that corresponding to the value of $h = h$ (actually used) $+ d$. These curves were derived by calculation by the methods given in Chapter III.

Sometimes the tubular source is composed of a number of separate sources placed in a line. If this is so, the distance between the adjacent active ends should not exceed $h/2$, although with an odd number of tubes of five or more, a spacing of *h* is just permissible.[16] Also two tubes only, with an inactive gap, form a bad approximation to a continuous line source.[16]

As in other methods of radium therapy, the relative depth dose obtained depends upon the distance between the radium and the nearest surface of the lesion. The effect of increasing the

" distance " is illustrated in Fig. 64 (*a*) which shows the variation of dose with depth for various values of *h* between 2 mm. and 4 cm. in the case of a 50 mgm. tube of radium, of 5 cm. active length, filtered by 1·5 mm. platinum. In each case the dose is expressed in terms of that at the nearest surface of the lesion, which is taken as 100 per cent. It may be seen how poor is the depth dose for the smaller values of *h*. For this reason endeavour should be made to use the greatest possible value of *h*. To this end Tod[1] has used a device in which the rubber catheter used for carrying the tubes *in situ*, is surrounded by a thin rubber balloon which is inflated when the apparatus is satisfactorily in place within the rectum. Of course, as *h* is increased, the dosage-rate at the tumour surface gets less and the treatment time must be correspondingly longer. The fall in the surface dosage-rate with increase in *h* is shown in Fig. 64 (*b*) for the same line source as before.

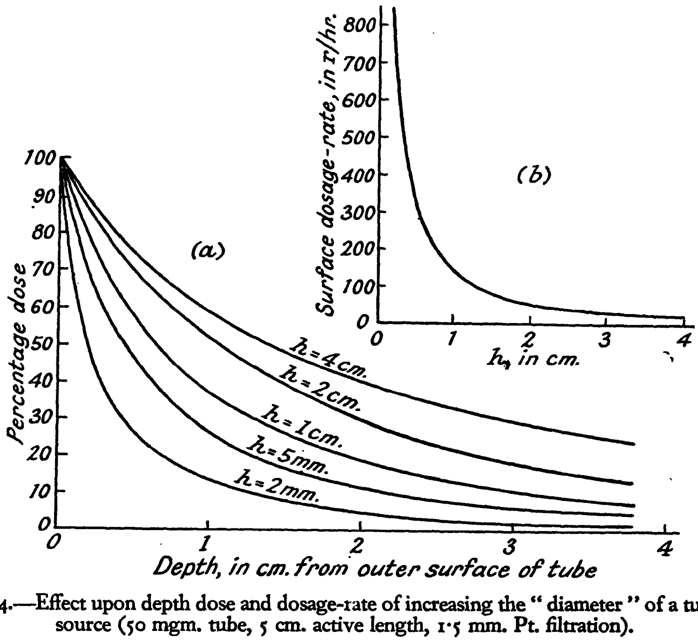

FIG. 64.—Effect upon depth dose and dosage-rate of increasing the " diameter " of a tubular source (50 mgm. tube, 5 cm. active length, 1·5 mm. Pt. filtration).

Rectilinear sources are also used for cavitary irradiation of the œsophagus. Similar principles apply and the value of *h* is usually kept as great as possible by having the radium within the largest rubber tube that will pass the stricture. The screenage of the

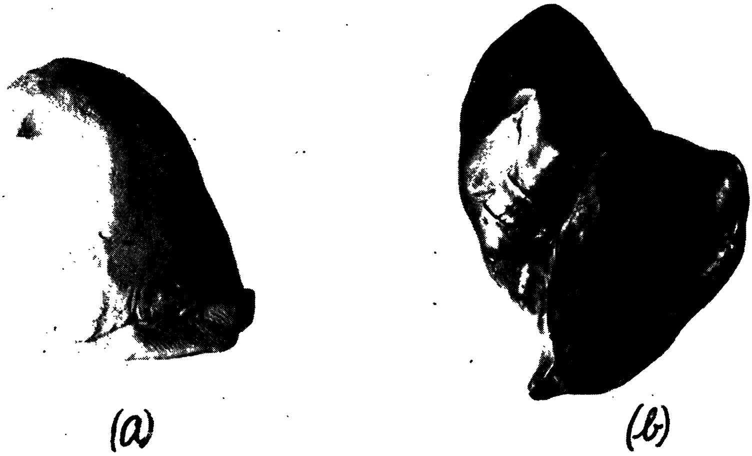

FIG. 61.—Intra-cavitary applicator for irradiation after fenestration of the antrum.
(*a*) Plasticine filling into which radioactive sources are introduced.
(*b*) The shellac applicator cast to fit the cavity.

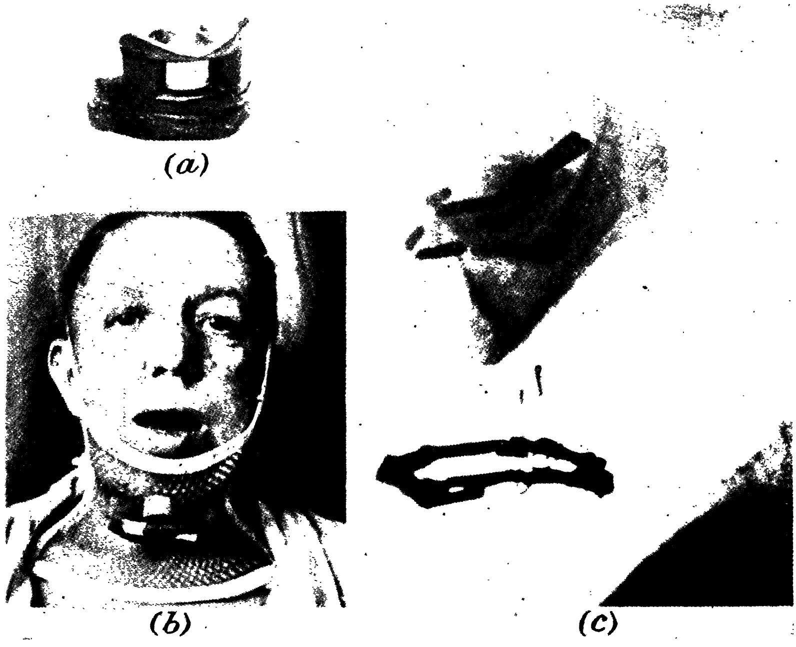

FIG. 65.—" Sandwich " applicator for the irradiation of the floor of the mouth.
(*Paterson and McVicar.*)
(*a*) Cavitary portion.
(*b*) External portion in position.
(*c*) Radiograph showing relative positions of the applicators and tissues.

radium used is usually at least 1·5 mm. platinum and the rubber outer tube serves to absorb the secondary radiations from the metal. Similar methods are used for determination of the dosage.

It is fairly obvious that adequate dosage can hardly be given in these cases by cavitary treatment alone, and it is usual to combine this form of treatment with X-radiation. It is likely that future physical studies of the volume distribution of radiation in such combined methods will materially aid future progress in the treatment of malignant disease at these sites.

(*c*) IRRADIATION OF THE MOUTH.* Intra-buccal, plaque-like applicators are used for lesions of the palate, the alveolus, and very superficial lesions of the floor of the mouth or buccal surface of the cheek.[17] In addition, some lesions, such as those involving the floor of the mouth or cheek rather extensively, may be treated by means of a sandwich applicator. One side of this will be an intracavitary applicator, the other side a surface applicator. To achieve satisfactory conditions of homogeneity, the Paterson and Parker rules should be used to determine the distribution of radium upon the applicator; those already discussed (Chap. V) for single-plane applicators and those that will be discussed later in this chapter for sandwich applicators. The construction of the applicators themselves may follow the lines already described in Chapter V.[17] Fig. 65 illustrates a typical sandwich applicator for the irradiation of the floor of the mouth by means of two parallel rings of radium.[17] The cavitary portion illustrates the type of mould that is usually used alone for superficial lesions of the alveolus or palate.

4. Interstitial Methods of Irradiation[1]

In this method of radium therapy, radium needles or radon seeds are inserted directly into the tissues. The method is used especially in the treatment of carcinoma of the tongue, lips, tonsils, buccal mucosa, skin (including epithelioma of the penis), the female urethra and in the treatment of the breast, either as the sole method or in association with excision, surface irradiation or X-radiation.

In common with the other methods of radium therapy, the aim should be so to distribute the radium sources that the tissues to be treated are irradiated as uniformly as possible. It is inevitable, however, that the tissues in actual contact with a needle receive a dose very much in excess of that over the whole volume so that the question of local tolerance must be considered. The magnitude of such " high-spots " depends upon the quantity of radium concentrated in the individual sources.

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* A detailed account of the intra-oral radium treatment of cancer of the mouth has been given recently by Dr. J. R. Nuttall (*British Journal Rad.*, Vol. 16, 1943, pp. 45 and 72).

Paterson[18] considers the following maximal concentrations to be safe :—

(1) 0·66 mgm. per linear cm. of needle filtered by 0·5 mm. Pt. for 10 days.

(2) 1·0 mgm. per linear cm. of needle filtered by 0·5 mm. Pt. for 6 days.

(3) 1·3 millicuries in a gold radon seed as a permanent implant.

Obviously, the larger the number of radioactive foci used while the same dosage-rate is maintained, the lower is the strength of the individual " high-spots."

The problem of the determination of dosage in interstitial radium therapy is presented in two distinct forms. It may be required to determine the dosage due to an arrangement of radium needles which is decided upon solely by the surgeon on a basis of his past experience, or to specify a distribution of radium sources such as to achieve a desired condition of homogeneity of radiation and a certain minimum dosage-rate. The latter attitude is the more recent and is still not adopted very widely, but from all points of view it is the most desirable, since it involves very much less total work on the part of the physicist, while it ensures irradiation with known physical conditions which can be controlled from the beginning of treatment.

5. Measurement and Calculation of Interstitial Dosage

The determination of the dosage due to a given arrangement of radium needles may be carried out by means of calculation or measurement. Since it is inevitable that high spots occur in regions adjacent to the radium sources, one is concerned not so much with the average dose as with the minimum dose received by the treated tissues. This is so even when an optimum degree of homogeneity has been achieved. If the minimum dose is sufficient to bring about the desired clinical result, that at any other point must be sufficient also, provided it is not so great as to produce undesirable reactions such as necrosis.

In practice calculation possibly lends itself to more accurate results than does direct measurement. As a general rule, the distances involved are much smaller than in other forms of radium therapy, and points have to be investigated which are quite close to radium sources. The rate of change of dosage with distance at these points is very great, so that measurements, made even with quite small ionization chambers, often may not be of a very high order of accuracy.

It is sufficiently accurate to assume that the values calculated for points in air near a radium source are equal to those at the same points when the source is embedded within tissues. It is not possible to make satisfactory allowance for secondary beta radiations from the metal walls of the sources. Curves expressing the relation between dosage and distance from radium needles or radon seeds may be calculated as illustrated in Chapter III. In practice it will be necessary to know the relative positions and orientations of all the radium sources distributed throughout the tumour mass. Then, for any specific point within the mass, the contribution due to each source may be determined from the appropriate dosage curve; the sum of these contributions is the total dosage at the point. It may be seen that the process is a long and tedious one, even for a determination of just the minimum dosage.

The true spatial distribution of the radium sources within the tissues may be determined precisely by means of a " radium implant reconstructor " described by Parker and Meredith.[19] Two types of apparatus are used. In one case the apparatus is based upon two radiographs of the implanted tissues, one at right angles to the other, and in the alternative method, use is made of stereoscopic radiographs. For further details the original work should be consulted. When the disposition of the needles has been reconstructed in this manner, the calculations may be made quite accurately, or, of course, if the reconstruction is made with the actual sources, the dosage may be measured. Such procedure as this, however, is not at all common practice, and at the present time the information available concerning the intuitive arrangements of needles used is most often so scanty as to be of little use for accurate assessment of dosage.

Because of the difficulties and tedious work obviously involved, relatively little information has been obtained so far concerning the dosage delivered in interstitial radium therapy. At Westminster Hospital we have used more simple, but possibly less accurate, methods of assessing the dosage delivered in some interstitial methods. Thus Wilson and Cade[20] made approximate measurements of the minimum dosage delivered in the interstitial irradiation of carcinoma of the tongue. Post-mortem tongues were needled in a manner as nearly as possible identical with the needling used in a number of specific cases in which satisfactory clinical results had been obtained. Using small, spherical, condenser chambers of 7 mm. external diameter, measurements were made at those points on the surface of the tongues where the dosage-rate was a minimum. It was found that the minimum dosage-rate in the different cases ranged between 28·4 *r*/hr. and 76·5 *r*/hr., so that for the overall treatment time of 168 hours (7 days), the minimum total dose delivered ranged from 4,780 *r* to 12,800 *r*. The wide range covered by these values is significant of the difficulty of obtaining similar dosage conditions in different cases when the sources are arranged by intuitive methods. Although the chambers used were quite small, they are, even so, really too large for this type of measurement. Those described by Spiers and La Touche[21] (see Fig. 45, p. 98) should be much more suitable.

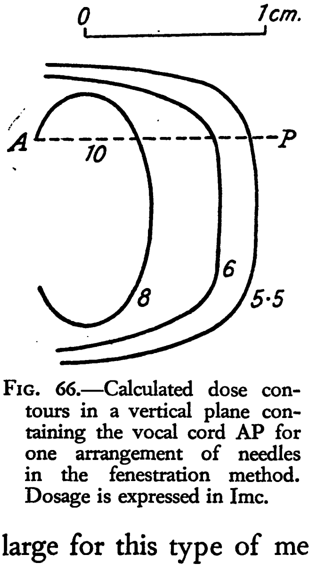

Fig. 66.—Calculated dose contours in a vertical plane containing the vocal cord AP for one arrangement of needles in the fenestration method. Dosage is expressed in Imc.

We have made a similar examination of the dosage delivered in the fenestration method of irradiating carcinoma of the larynx both by calculation[22] and by direct measurement.[1] The fenestration method has been described in detail by Cade,[1] and has small variations depending on the extent of the disease. The case examined was that in which only the thyroid cartilage is fenestrated and seven 1 mgm. needles (overall length 24·5 mm.; active length 16·3 mm.; filtration 0·8 mm. Pt.) are placed closely side by side in the form of a palisade. A post-mortem larynx was examined and measured carefully so that the mean dimensions of the organ and the relative positions of the radium within it were known. The dosage distribution in the region of the vocal cord was then determined by means of a large-scale diagram and the calculated dose contours for the needles. The result is shown in Fig. 66, which represents a plane vertical section through the vocal cord AP; the dosage values are given in Sievert units. The minimum dosage delivered to the cord (at the posterior end, in the region of the arytenoid) in the treatment time of seven days is of the order of 7,200 *r*. The "average" value over the whole cord is of the order of 10,800 *r*. The distribution of radiation suggests that the arrangement of needles might be improved to give greater homogeneity. This has been done, in fact.[1]

Measurements of the dosage were made by using the fenestrated larynx in a manner similar to that described for the tongue. These experiments, which had a very low order of accuracy because of the size of the ionization chambers used, indicated that the dosage at the cord was of the order of 8,000–12,000 *r*, in fair agreement with the calculations.*

Lederman and Mayneord[23] have published similar, but more detailed, calculated radiation distributions for the same technique when it is based on the use of longer needles. Their general conclusions are similar to those stated above, and they also point out that "in a fenestration it would seem desirable on physical grounds to use the greatest length of needle possible" because "the vertical length of the volume of high dose is, in fact, determined very largely by the active length of the needles."

Some most interesting work has been described by Evans and Griffith[24, 25] in which the dosage of interstitial radium treatments of primary carcinoma of the breast and of secondary carcinoma of the

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* Since the above was written "A Consideration of Dose Distributions in the Treatment of Intrinsic Carcinoma of the Larynx by Radium Implantation" has been published by J. Morton, L. H. Gray and G. J. Neary (*British Journal Rad.*, Vol. 17, 1944, p. 204). These authors have made a most detailed study of the dose distributions obtained by various radium implantation techniques based on a close examination of eighteen larynges (male and female) so that their results are more generally applicable than those given above. From their results it may be seen that the dose levels given above are in considerable excess of those in an average case, and it is apparent that this is chiefly because the larynx, for which our values are derived, was very small. In a technique using 8, 1 mgm. needles, they found a dose of 7,250 *r* at the anterior end of the cord, falling to 3,300 *r* in the region of the arytenoid.

The data given by these authors will serve as a most useful guide to modifications which might be made in cases where the disease shows extension into the sub-glottic region or posteriorly along the vocal cord.

TABLE 21.—*Quantities of Radium to deliver a minimum of one Erythema Dose (1,000 r) in various volumes. Interstitial Sources. Filter 0·3–0·5 mm. Pt. Needles left in place for Four Days or longer. (E. H. Quimby)*

Volume in c.c.	10	20	30	40	60	80	100	125	150	200	250	300	350	400	450	500
Mgm.-hours per erythema dose .	275	380	470	530	650	750	845	955	1,060	1,250	1,410	1,590	1,730	1,870	1,990	2,110
Millicuries destroyed per erythema dose.	2·1	2·9	3·5	4·0	4·9	5·6	6·4	7·2	8·0	9·4	10·6	12·0	13·0	14·0	15·0	16·0

lymph-nodes of the neck, was controlled by means of direct measurement of dosage-rate at the skin. In the treatment of carcinoma of the breast the radiation source was a flat "grid" of specially designed needles filled with radon and in the case of carcinoma of the lymph-nodes of the neck a palisade of radium needles (linear density 1·5 to 2·0 mgm./cm.) was used. The skin dosage-rates, which were the minimum values, were of the order of 0·5–0·6 *r*/min. Treatment times were of the order of 300 hours and an interesting feature of the work is the high dosage levels which were reached in those parts of the tumour near the radiation source without apparent harmful sequelæ. In some cases of primary carcinoma of the breast, for instance, tissue doses of the order of 16,000–23,000 *r* were given.

6. Dosage Systems for Interstitial Therapy

As we have already pointed out, it is more satisfactory to devise dosage systems whereby specific arrangements of radioactive foci are used such that the dosage is known and controlled from the beginning of treatment.

In the United States such a dosage system has been investigated by Quimby and her co-workers at the Memorial Hospital, New York, [26, 27, 28.] This system is based upon the idea of irradiating spherical volumes of tissue, throughout which the radioactive foci are uniformly distributed to give a certain minimum dose. Slight variations from symmetrical or uniform distributions, when several foci are used, do not produce unreasonably large variations in this minimum dose. Thus a dosage table (such as Table 21) was developed by means of which it is possible to determine the number of milligram-hours (or millicuries destroyed) necessary to deliver a specific dose within a sphere of any reasonable size. The dose taken as a standard amount was the skin erythema dose already referred to (Chap. III) and approximately equivalent to 1,000 *r*. If the dosage is required for volumes in between the values given in the table, it may be interpolated from a graph representing the table. Such tables have been widely employed by American radium therapists ever since their appearance.

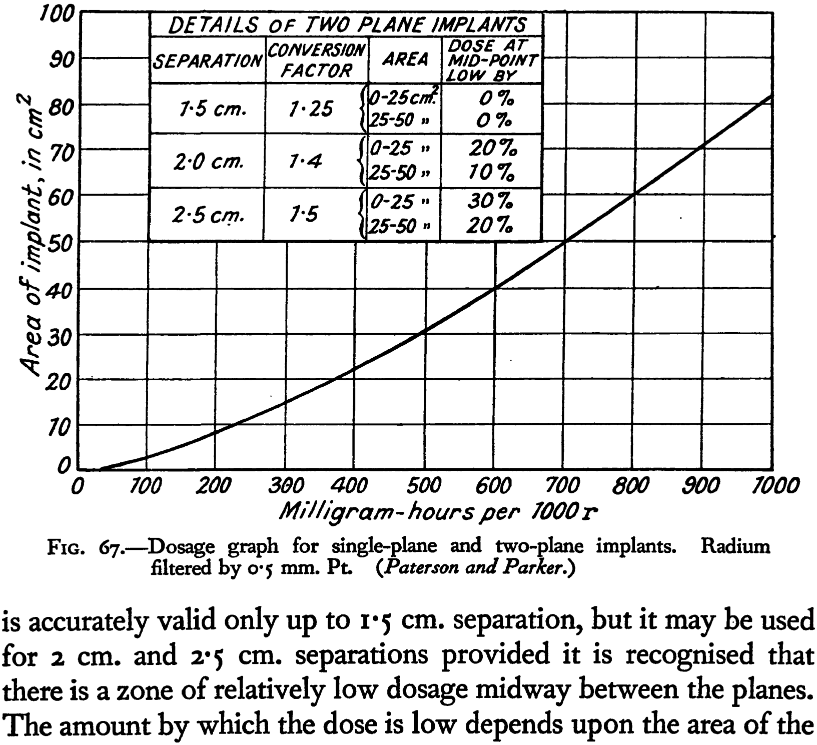
In this country Paterson and Parker[18, 29] have given an account of a most valuable dosage system for interstitial radium therapy which we shall consider in some detail. Lawrence[30] in Canada has also considered the question.

7. Paterson and Parker's Interstitial Dosage System

The dosage system worked out by Paterson and Parker[18, 29] for interstitial radium therapy, is similar to that developed by them for superficial work in that a number of simple distribution rules have been deduced as a simplification of the results obtained from much detailed calculation. As before, and upon the same basis, the dosage is expressed in röntgens. The calculations refer to air and no allowance is attempted for secondary beta radiation. The system is based upon two quite separate types of implantation, namely, (1) planar implants and (2) volume implants.

(1) PLANAR IMPLANTS. (*a*) *Physical Details.* The use of planar implants is a development from the surface dosage system described in Chapter V and the radium is arranged either as a single plane of needles or seeds, or as multiple parallel planes. Paterson[18] chooses the technique for implanting under a lesion spreading along a surface or where a lesion can most easily be dealt with by " sandwiching " it between two parallel planes of radium, so arranged that the distance apart is small relative to the area of each plane.

The dosage graph to be used for such planar implants (Fig. 67) gives the relation between the *area* of the slab of tissue to be implanted and the *total amount* of radium (in milligram-hours) required to give 1,000 *r* in the immediate vicinity of a single plane or in the volume of tissue between two planes. For a single plane the graph is correct, except for corrections for filtration, and gives the dosage within a layer of tissue 1 cm. thick, of which the plane is the centre. When the radium is distributed on two parallel planes, the graph reading has to be increased (except for 1 cm. separation) by a factor depending on the separation of the planes, according to the table shown on the graph. The two-plane method is accurately valid only up to 1·5 cm. separation, but it may be used for 2 cm. and 2·5 cm. separations provided it is recognised that there is a zone of relatively low dosage midway between the planes. The amount by which the dose is low depends upon the area of the treated slab, the values being given in the table on the graph of Fig. 67.



DETAILS OF TWO PLANE IMPLANTS

SEPARATION	CONVERSION FACTOR	AREA	DOSE AT MID-POINT LOW BY
1·5 cm.	1·25	0-25 cm.² 25-50 "	0 % 0 %
2·0 cm.	1·4	0-25 " 25-50 "	20 % 10 %
2·5 cm.	1·5	0-25 " 25-50 "	30 % 20 %

FIG. 67.—Dosage graph for single-plane and two-plane implants. Radium filtered by 0·5 mm. Pt. (*Paterson and Parker.*)

Because of a number of simplifications of the original surface applicator rules (p. 111, Chap. V) that are possible for these implants, the distribution rules may be modified to the following :—

(*b*) *Distribution Rules for Clinical Application* (*Planar Implants*). (i) On a single plane the radium should be arranged such that for areas under 25 cm.^{2} two-thirds, and for areas of over 25 cm.^{2}

one-half, of the total radium is placed round the periphery of the area, and the remainder evenly over the area itself.

(ii) A row of parallel needles with active ends crossed by a needle or needles at right angles to them is a common arrangement. If it is impossible to cross the ends of such an implant, 10 per cent. must be deducted from the area for graph reading purposes for each " uncrossed " end.

(iii) Needles in such a series of parallel lines should not be more than 1 cm. from each other or from the crossing ends. Similarly, the spacing of radon seeds should not exceed 1 cm.

(iv) In two plane-implants, the separate planes should be arranged according to (i), (ii) and (iii) and should be parallel to each other.

(v) If two planes differ in area, the area used for dosage graph purposes is the average of the two and the total amount of radium is divided *pro rata* to each area.

These rules are based upon a number of considerations discussed in full in the original paper.[29] It is obvious that it is impossible to obtain uniform dosage throughout a slab of tissue by means of a single radioactive plane, but experience has shown[18] that clinically satisfactory results are obtained within a slab of tissue 0·5 cm. thick on either side. Thus, provided the dosage graph is drawn to give the amount of radium required to produce a stated dose at 0·5 cm. from the plane, the stated dose is the minimum throughout the slab.

(2) VOLUME IMPLANTS.* The planar type of implant described above, although very valuable, cannot readily be extended to cover the general field of interstitial irradiation. Parker has therefore planned a more general scheme, a mathematical approach that had been used by Souttar[31] for the special case of a sphere, being extended to the treatment of various shapes so that general, empirical relations might be obtained, enabling one to build up a universal scheme of dosage for interstitial therapy.

(*a*) *Physical Aspects.*[29] The method involves the distribution of a hypothetical radioactive fluid within the volume to be treated, in such a way that the resultant dosage-rate is approximately constant throughout. Thus a mathematical study was made of the radiation fields created by distributions of a hypothetical radioactive fluid throughout a number of different shapes (the sphere, circular and elliptic cylinders, ellipsoids and rectangular parallelepipeds), restricting the treatment to cases in which two regions of different fluid density are permitted. These two regions form inner and outer parts of the whole volume, a so-called core and rind. The investigation showed that the mean dosage-rate within solids of the same volume and radium content, is independent of the shape, except for a small correction factor determined by the elongation of the shape, and the dosage is given by the formula :—

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* The following account follows very closely the text of the original paper by Paterson and Parker.

$$\text{Mgm.-hours per } 1{,}000\, r = 21{\cdot}57 .\, V^{\frac{2}{3}}\, e^{0{\cdot}07\,(E-1)} \quad . \quad . \quad . \quad (1)$$

where V is the volume concerned in c.c. and E is the ratio

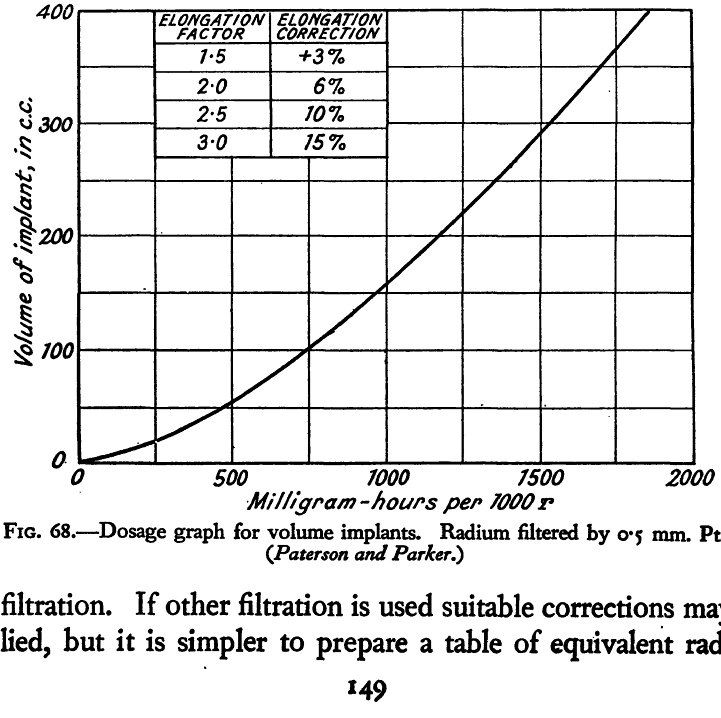
$$\frac{\text{longest principal axis}}{\text{shortest principal axis}}.$$

When the generalisations are transcribed into particular arrangements of discrete radioactive sources, the question of " high-spots " arises again and a new outlook towards the dosage has to be adopted. Since it is the minimum dose, rather than the average dose, which is clinically important when the two are not approximately equal, the results must be translated in terms of minimum dose. In order that this technique might be comparable with that for planar implants, the minimum dose for a volume implant was taken 10 per cent. higher than the absolute minimum in the effective volume. The modifications to dosage-rate distribution, introduced by the condensation of the hypothetical fluid to discrete sources, were derived by treating each case empirically by repeated application of dosage calculations for individual needles or point sources. In this way the pertinent dosage and distributions rules were derived.

In practice, by reason of the various limiting conditions that have to be fulfilled, the greater part of an implanted volume receives a dose some 20 per cent. higher than the minimum dose and in the region of the " high-spots " the dose may be many times the minimum dose. It is thus not possible to realise a distribution that is very close to the ideal and Parker points out that " the final distributions of dose are, in a sense, so inhomogeneous that the system has to be defended against much simpler methods, involving complete peripheralisation of the radium." It may be shown quite easily, however, that in the peripheralisation method, the high-spots are more severe and tend to fuse together, and the method becomes progressively less satisfactory as the volume increases, whereas this system is capable of dealing successfully with very large volumes.

The distribution rules and dosage graph, formulated as a result of the investigations outlined above, form the data which are directly applied in actual practice. The method is applicable when the tumour bearing mass can be implanted throughout so as to completely surround the tumour, and the dimensions of the volume are of similar magnitude, *e.g.*, a growth in the substance of the tongue, a gland in the neck, or a sarcoma of the soft parts. An attempt has to be made to include the volume within one of the geometrical shapes that have been studied, but in practice, since straight radium needles are used, the cylinder proves to be the most useful shape. A spherical arrangement can really only be achieved with radon seeds and the cuboid form is obtained as multiplanar implants rather than by direct application of the volume rules.

The relation between the milligram-hours for 1,000 *r* and the volume to be implanted is given in the graph of Fig. 68 for 0·5 mm. Pt. filtration. If other filtration is used suitable corrections may be applied, but it is simpler to prepare a table of equivalent radium



ELONGATION FACTOR	ELONGATION CORRECTION
1·5	+3%
2·0	6%
2·5	10%
3·0	15%

FIG. 68.—Dosage graph for volume implants. Radium filtered by 0·5 mm. Pt. (*Paterson and Parker.*)

contents for 0·5 mm. Pt. filtration for the particular stock of needles available. In addition a correction factor must be applied to the number of milligram-hours to take into account the elongation E. These factors are given in the table included in Fig. 68.

(*b*) *Distribution Rules for Clinical Application* (*Volume Implants*).[18] The volume is considered as consisting of a " rind and core." In a sphere the rind is the surface of the ball, in a cylinder it consists of a belt and two flat ends, in a rectangular figure it is the six faces. The core is the whole volume to be irradiated. The whole of the radium quantity determined from the volume-dosage graph is divided into eight parts, and is distributed as follows for the various shapes :—

Sphere : Shell 6 parts ; core 2 parts.
Cylinder : Belt 4 parts ; ends 1 part each ; core 2 parts.
Cuboid : Each face 1 part each, core 2 parts.

The cuboid may alternatively be treated as a multiplanar implant in which the radium is subdivided : Each outer plane 3 parts ; each inner plane 2 parts.

The radium is actually distributed as follows :—

(i) The radium on each surface should be spaced as evenly as possible and the number of needles should, if possible, be such that not more than 1–1·5 cm. of tissue separates any needle from its nearest neighbour.

(ii) The radium for the core should be spread as evenly as possible throughout the whole volume, and should not all be at the centre.

(iii) In the multiplanar cuboid the radium is arranged on the planes as for planar implants.

(iv) The belt of a cylindrical implant should consist of not less than eight needles, the core of not less than four.

These rules may also be modified in two ways of value in practice without serious loss of accuracy :—

(v) In some types of cylindrical implant it is impractical to close one or both ends of the volume. In such cases, the volume, as determined by the active length of the belt, must be reduced by 7½ per cent. for each open end and the radium divided into : belt 4 parts ; core 2 parts ; end 1 part ; or : belt 4 parts ; core 2 parts.

(vi) In the case of a lesion surrounding a cavity, *e.g.*, carcinoma of the rectum, it is impossible to implant radium into the core, but it is practicable to combine a cylindrical implant round the lesion with an intra-cavitary applicator. The " two-parts " of radium for the core may then be in the centre of the volume, provided it is enclosed in a container (rubber or otherwise) whose diameter is equal to at least one-half the diameter of the total cylinder.

Oddie[32] has considered the extension of this dosage system to the irradiation of cones, prisms, pyramids or tetrahedra of tissue. The same volume-dosage graph can be used apparently, provided a correction is added to the total milligram-hours determined from the graph. The correction to be added depends upon the relative lengths of the sides and diameters of the figures ; the actual values of the corrections given by Oddie are set out in Table 22. The following distribution rules, which have been found to give reasonably homogeneous dosage, should then be applied :—

In all cases given, divide the total radium into ten parts and allot these as follows :—

TABLE 22. *Percentage Corrections to be added to to the mgm.-hours determined from the volume-dosage graph (Fig. 68) to allow for shape of region of tissues treated (Oddie).*

Shape	Relative lengths of sides		Per cent. correction
	Sloping side	Base diameter	
Cone	3	2	7
	3	1	17
	2	3	58
	2	1	8
	1	1	12
	Sloping edge	Each side of base	
Pyramid	3	2	20
	3	1	33
	2	1	22
	1	1	37
	Sloping edge	Each side of base	
Tetrahedron	3	2	48
	3	1	91
	2	3	79
	2	1	64
	1	1	39

Shape	Relative lengths of sides				Per cent. correction
	Length	Sides of end triangle			
Prism	3	3	3	2	36
	3	3	3	1	100
	3	3	2	2	53
	3	2	2	2	38
	3	2	2	1	81
	3	1	1	1	80
	2	3	3	3	18
	2	3	3	2	28
	2	3	3	1	78
	2	3	2	2	38
	2	2	2	1	58
	2	1	1	1	53
	1	3	3	3	26
	1	3	3	2	26
	1	3	3	1	56
	1	3	2	2	30
	1	2	2	2	19
	1	2	2	1	35
	1	1	1	1	25

Cones.

Circular edge of base	4 parts
Surface of base	2 parts
Sloping surface	2 parts
Core	2 parts

The radium on the sloping surface should be in needles of uniform linear strength, half of these needles running from the edge of the base to the point of the cone, and half running only half-way up from the base.

Prisms.

Nine edges of the prism	4 parts
Three rectangular faces	1 part each
Two triangular faces	½ part each
Core	2 parts

Pyramids.

Eight edges of the pyramid	5 parts
Four triangular faces	½ part each
Square base surface	1 part
Core	2 parts

Tetrahedra.

Six edges of the tetrahedron	6 parts
Four faces	½ part each
Core	2 parts

In all cases the radium along the edges should be of uniform linear strength, and that on the faces, and in the core, should be distributed as evenly as possible.

Convenient formulæ deduced by Oddie for the calculation of the volumes involved are given in Appendix IV.

Referring to the original system due to Paterson and Parker, the former[18] says " there are few situations in which it is not possible to devise a potentially satisfactory tissue implantation along one or other of the lines indicated, and experience has shown that both are of real clinical value."

The practical application of the methods can be illustrated best by giving a number of concrete examples which are taken from the original work. It is pointed out[18] that radium made up in the commonly used linear densities of 1·0 mgm. and 0·66 mgm. per cm. active length, can be employed fairly easily for single plane or volume implants of relatively large volumes. For small volume or multiplanar implants, however, radium of lower linear density is practically essential if it is desired to retain a seven- to eight-day duration of treatment. For this purpose needles of only 0·33 mgm. per cm. have been designed, *i.e.*, 0·5, 1·0 and 1·5 mgm. to 1·5, 3·0 and 4·5 cm. active length.

8. Typical Applications of The Paterson and Parker Methods.

(A) EPITHELIOMA OF FACE—SINGLE PLANE IMPLANT[18] (Fig. 69A). It is decided to treat a relatively flat epithelioma of the cheek to 7,000 *r* by means of a single-plane implantation undercutting the lesion so that the implant is at about 0·5 cm. from the surface. The size of the lesion is approximately 4 × 5 cm. and a rectangular implant of 6 × 7 cm. is decided upon, *i.e.*, area to be treated = 42 cm.^{2}

For 42 cm.^{2} area, 1,000 *r* is equivalent to 625 mgm.-hours at 0·5 mm. Pt. filter (Fig. 67), *i.e.*, 7,000 *r* = 4,375 mgm.-hours.

Approximate treatment time 7 days. ∴ Approximate radium required = 26 mgm.

Good distribution: Active periphery (26 cm. total) with 0·5 mgm. per cm. and 6 added bars, each with $\frac{2}{3}$ × 0·5 mgm. per cm., *i.e.*, half of radium round periphery and half over the area.

Use 1 mgm. and 2 mgm. needles loaded 0·5 mgm. per cm. as shown in Fig. 69A.

Actual total radium = 24 mgm. Time of treatment = 182 hours.

Aliter. Use 2 mgm. and 3 mgm. needles loaded 0·66 mgm. per cm. Long sides have 2,2 mgm. needles each. Short sides 1,3 mgm. needle each; 4 added bars, each 3 mgm.

Total radium = 26 mgm. and treatment time = 168 hours.

(B) EPITHELIOMA OF BLADDER—RADON SEED IMPLANT[16] (Fig. 69B). The bladder, on being opened, was found to contain a fungating epithelioma, which, after diathermy removal, left a malignant base about 3 cm. in diameter. It was decided to treat to 6,500 *r*, a circle 4·5 cm. diameter as a single plane, submucous implant, with radon seeds (0·5 mm. Au. or Pt. filtration).

Area of treated circle = 15·9 cm.^{2}, *i.e.*, 1,000 *r* is equivalent to 310 millicurie-hours (Fig. 67). 6,500 *r* is equivalent to 2,015 millicurie-hours = 15·1 millicuries permanent implant.

Distribute two-thirds round the periphery and one-third over the area.

Use fifteen 1 millicurie seeds, 10 on periphery and 5 over the area (Fig. 69B).

(C) TUMOUR OF SKIN—TWO PLANE IMPLANT[18] (Fig. 69C). Lesion is a flat, plaque-like, solid implantation tumour of the abdominal wall. Size is approximately 5 × 6 cm. and apparently not more than 1–1·5 cm. thick. Not fixed deeply, too thick, however, for a single plane implant. Decided to treat to 6,000 *r* by a two-plane implant, one larger plane undercutting the lesion, but coming to the surface of the skin beyond the tumour, and a superficial plane in the surface of the lesion itself, as near the skin as possible.

First plane 6 × 7 cm., area = 42 cm.^{2} Second plane 5 × 6 cm., area = 30 cm.^{2}

Average area = 36 cm.^{2}

1,000 *r* is equivalent to 560 mgm.-hours (Fig. 67). Separation factor for 1·5 cm. = 1·25.

∴ 1,000 *r* is really equivalent to 560 × 1·25 = 700 mgm.-hours, or 6,000 *r* = 4,200 mgm.-hours or 25 mgm. for 7 days.

Dividing in the ratio of areas, plane 1 has 14·6 mgm. and plane 2 has 10·4 mgm.

Both planes have approximately half the radium round the periphery and half over the area. A suitable distribution with needles loaded 0·33 mgm. per cm. is given in Fig. 69C.

Total radium = 23·5 mgm. so that corrected treatment time is 179 hours.

(D) EPITHELIOMA OF ANUS AND RECTUM—VOLUME IMPLANT OF INTRACAVITARY TYPE[18] (Fig. 69D). Lesion is a primary epithelioma of the anus, growing about 5 cm. up the rectal wall and completely surrounding it. Decided to treat to a dose of 6,000 *r* by a cylinder surrounding the lesion plus a sorbo radium-containing tube along the centre of the malignant canal. Actual needles used for the implant consisted of hollow steel sheath needles, into which ordinary platinum needles are loaded. When loaded, the active length of these is 6 cm. (overall length = 8 cm.).

Implant is an elliptic cylinder, of height 6·5 cm., the elliptic axes being 5 cm. and 6 cm.

Volume = 153 c.c., but one end of the cylinder is open, so that

$7\frac{1}{2}$ per cent. is deducted, *i.e.*, effective volume is 141 c.c., whence from Fig. 68 1,000 *r* is equivalent to 923 mgm.-hours. Elongation correction is negligible, so that 6,000 *r* is equivalent to 5,538 mgm.-hours.

The radium thus subdivides:—

Belt (4 parts): 3,164 mgm.-hours = 18·1 mgm. for 176 hours.
End (1 part): 791 ,, ,, = 4·5 mgm. for 176 hours.
Core (2 parts): 1,582 ,, ,, = 36·2 mgm. for 47 hours.

The cavitary tube (core) can only be left in position for 48 hours, after which the obstruction becomes severe. Hence the time for the core and the needle implantation are different.

Radium actually used was:—

Belt: Six sheath needles, each containing one 2 mgm. and one 1 mgm. needle.

End: Two 1 mgm. needles and two 1·33 mgm. needles.

Core: Three 13·33 mgm. tubes in 1 mm. Pt. containers, equivalent to 36 mgm. at 0·5 mm. Pt. Diameter of sorbo tube containing these is 2·5–3·0 cm. (Fig. 69D).

(E) EPITHELIOMA OF FLOOR OF MOUTH—VOLUME IMPLANT[18] (Fig. 69E). The centre of the lesion is in the region of the frenum of the tongue, and the growth extends forwards into the floor of the mouth, and upwards into the substance of the tongue. Stitching the tongue down to the floor of the mouth, this type of lesion lends itself to a volume implant as a vertical cylinder, with needles in the lip as the anterior portion of the belt, and both ends crossed. The upper end is the dorsum of the tongue, the lower submental. Proposed dose 6,000 *r*.

The implant is an elliptic cylinder 4·5 × 4 cm., of height 3·5 cm. Volume = 49·4 c.c.

Thus 1,000 *r* is equivalent to 450 mgm.-hours (Fig. 68) and no corrections are needed. ∴ 6,000 *r* = 2,700 mgm.-hours = 16 mgm. for 170 hours approximately.

This radium is divided as follows:—

Belt (4 parts): 8 mgm.; use 1 mgm. needles each with 3 cm. active length.

Core (2 parts): 4 mgm.; use 1 mgm. needles also.

Each end (1 part): 2 mgm.; use 0·5 mgm. needles, 1·5 cm. active length or two 0·5 mgm. needles and one 1 mgm. needle (Fig. 69E).

(F) EPITHELIOMA OF TONGUE AND ALVEOLUS—THREE-PLANE IMPLANT (Fig. 69F). The lesion is a bulky epithelioma of the side of the tongue, involving the floor of the mouth and reaching upwards on to the lower alveolus and just into the cheek. This could be treated as a volume implant as in the last example, but the presence of bone makes a volume implant by three planes more appropriate. Proposed to deliver 6,000 *r*.

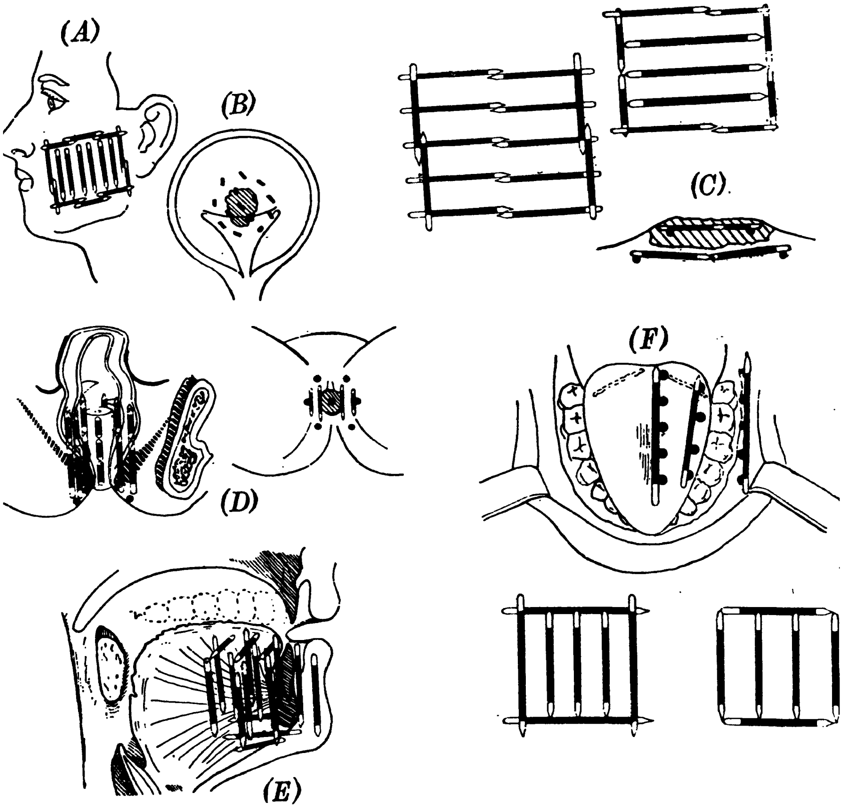


FIG. 69.—Typical examples of the application of Paterson and Parker's interstitial dosage systems. (*Paterson and Parker.*)

Area of each plane = 4·5 × 4·5 cm. Separation of planes = 1·75 cm., *i.e.*, volume = 71 c.c.

Thus 1,000 *r* is equivalent to 580 mgm.-hours (Fig. 68). Elongation factor = 1·3. Elongation correction = 2 per cent.

So that 6,000 *r* = 6 × 580 × 1·02 = 3,552 mgm.-hours.

For a time of 148 hours, 24 mgm. of radium are needed. This is divided into 9 mgm. on each side plane and 6 mgm. ($\frac{2}{3} \times 9$) on the central plane.

All the planes are less than 25 cm.^{2} so that the distribution on the planes is two-thirds around the periphery and one-third over the area. Using needles of 0·33 mgm. per cm. activity, the arrangement of needles is shown in Fig. 69F.

(G) Irradiation of a Cone, Base 6 cm. Diameter, Sloping Side 6 cm.[32] To deliver a dose of 6,000 *r*. Volume = 48·9 c.c. Correction for shape = + 12 per cent. (Table 22). ∴ 1,000 *r* is equivalent to 509 × 1·12 = 570 mgm.-hours (Fig. 68).

Thus 6,000 *r* = 3,420 mgm.-hours, say 30 mgm. for 114 hours.

The radium is divided into :—

Edge of base (4 parts) . . .	12 mgm.
Surface of base (2 parts) . . .	6 mgm.
Sloping surface (2 parts) . .	6 mgm.
Core (2 parts)	6 mgm.

(H) Irradiation of Prism, Length 6 cm., Triangular Section 3 cm. each Side.[32] To deliver a dose of 6,000 *r*. Volume = 23·4 c.c.

Correction for shape = + 53 per cent. (Table 22).

∴ 1,000 *r* is equivalent to 311 × 1·53 = 476 mgm.-hours (Fig. 68).

∴ 6,000 *r* = 2,856 mgm.-hours, say 30 mgm. for 95 hours.

The radium is then distributed into :—

Edge of prism, total length 36 cm. (4 parts)	12 mgm.
Three rectangular faces (1 part each) .	3 mgm. each
Two triangular end faces ($\frac{1}{2}$ part each) .	1·5 mgm. each
Core	6 mgm.

If low concentration needles are not available it will be necessary to use larger total quantities of radium in order that a satisfactory distribution may be made. This would necessitate a reduction in the time of implantation with possible tissue tolerance limitations.

As Paterson has remarked,[18] one of the greatest difficulties is the actual process of surgical implantation in accord with a pre-arranged scheme, but he finds that with practice and care, it is possible to conform to the schemes with quite an astonishing degree of accuracy. Moreover, provided the implant is not unbalanced, some degree of latitude is allowable in the disposition. The " implant reconstructor " already referred to is of great value for detecting possible errors in distribution that may be present. In any case, an attempted distribution upon this basis, even if errors do of necessity arise, is much to be preferred to the intuitive methods of approach.

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CHAPTER VII

RADIUM TELETHERAPY

1. Radium Teletherapy

As the name implies, radium teletherapy (or telecurietherapy) is the therapeutic use of a quantity of radium at a distance from the patient. The method as practised to-day is analogous to that of deep X-ray therapy, but it has developed rather as an extension of superficial radium therapy than as a copy of X-ray therapy. This point is well illustrated in the early work that was done between October, 1919, and April, 1921, in the cancer wards and research laboratories of Middlesex Hospital with 2·5 grams of radium element which was provided by the Ministry of Munitions. A detailed account of this work was given in the Medical Research Council's publication, " Medical Uses of Radium," Special Report Series 62, 1922, where it is seen that the radium was used quite close to the skin, the emphasis being on the use of a larger quantity of radium than before.

As we have seen, surface applicators consist of a number of radioactive foci arranged at a small, fixed distance from the skin, and distributed over the area to be treated. In radium teletherapy, the aim is to utilise a greater mass of radium in what is more or less one focus, in order that a greater radium-skin distance may be used to maintain the dosage-rate at an adequate level, while a more effective dose (relative to that received by the skin) is obtained at greater depths. The use of such large masses of radium makes it imperative that the apparatus holding the radium source provides an adequate degree of protection for the personnel working the apparatus, and only permits the exit of a relatively narrow cone of radiation. Thus the radium container, with thick walls of a dense metal to absorb the radiation, and an aperture to allow the exit of the " beam " of gamma radiation used for treatment, forms the most essential part of the apparatus used for radium teletherapy.

In practice, radium teletherapy represents an adaptation of many deep X-ray therapeutic principles to gamma ray therapy, but greater care is usually needed in the application, for a number of reasons which will be made plain later. Multiple ports of entry, for instance, are used, in order to make use of " cross-fire " to obtain greater homogeneity of radiation at a depth in tissue where the disease is located, and also to obtain the delivery of a larger total dose than is possible by means of a surface applicator, which, in effect, irradiates through a single port of entry only.

The method has a number of advantages over the other methods of radium therapy which may be listed as follows :—

(1) Operative intervention is avoided.

(2) Subject to certain conditions which we shall examine in what follows, accuracy of treatment is increased.

(3) Radiation may be delivered to the deepest parts of a tumour at an adequate dosage-rate.

(4) It is possible to deliver an increased total dose to a tumour without a corresponding increase in damage to normal structures.

(5) The actual situation of the disease is not quite so important.

(6) The treatment can be protracted or fractionated at will.

(7) The destructive effects on the lymphocytes are less than with surface plaques of lower radium content by reason of the more adequate protection provided.

Apparatus used for radium teletherapy has been variously called radium bomb, radium pack, or radium mass unit. The latter name is now more commonly used, although the other names are still used on occasion. The method owes much of its original development to the schools of radium therapy at the Memorial Hospital, New York, the Paris Radium Institute, and Radiumhemmet, Stockholm.[1, 2, 3] One of the earliest of serious attempts at its use in this country was begun at Westminster Hospital in 1928, where the method has undergone considerable evolution to reach its present form. Since 1934 many contributions to the method have been made by the Radium Beam Therapy Research,* housed at the London Radium Institute, whose workers have been able to approach the many problems involved in a manner more purely experimental than is possible in a large general hospital. At the present time, large mass units exist in many institutions which are studying the innumerable questions that still have to be considered.

For our present purpose it will suffice to describe one or two of the earlier types of radium mass units along with one or two of the modern units now in use. Such descriptions will show how the

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* The Radium Beam Therapy Research is now known as the Medical Research Council Radiotherapeutic Research Unit and is housed at Hammersmith Hospital, London, W.12.

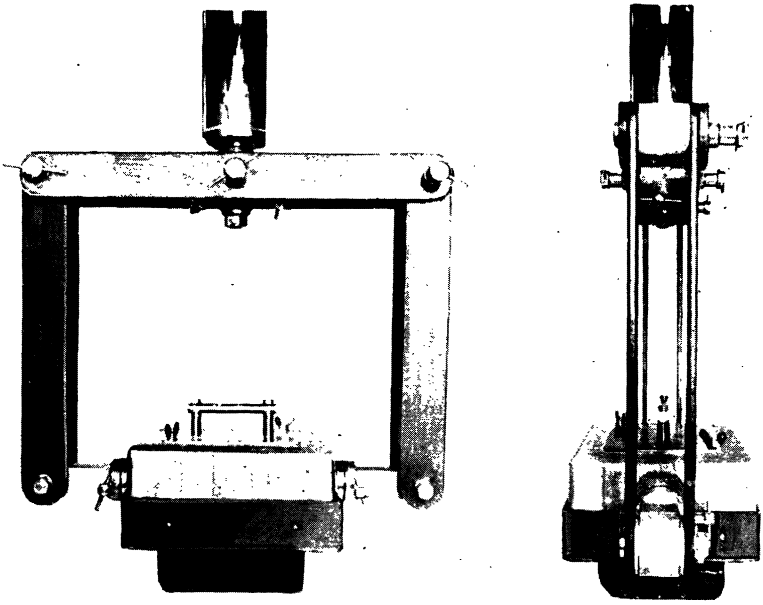
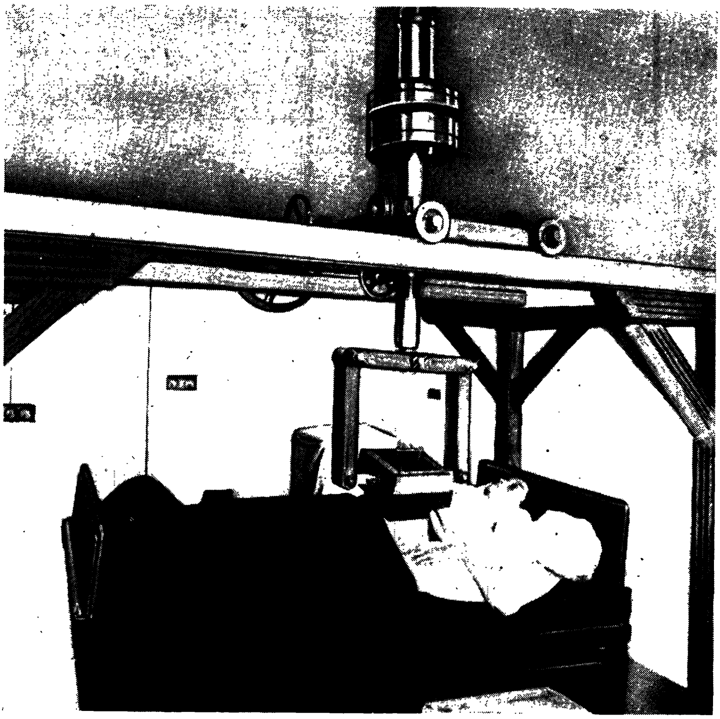


FIG. 70 (*a*). Early Paris unit. General features of the container.



design has been affected by our increase in knowledge of the requirements for satisfactory therapeutic application. The considerations which have directly and indirectly influenced the design have been :—

(*a*) Mobility and compactness of the unit.

(*b*) Physical character of the radiation " beam," which necessitates considerations of the radium focus and the absorbing material of the container.

(*c*) Safety of personnel as it is affected by the material of the container and the method of charging the container with the radium.

(*d*) Application of the beam to the patient, which is dependent in turn upon (*a*) and (*b*) as well as upon methods of directing the beam and of moving or fixing the patient as required.

2. Early Mass Units

(*a*) THE PARIS UNIT.[4] This was one of the earliest forms of apparatus used for radium teletherapy. Its general features and method of application to the patient are illustrated in Fig. 70. The radium container was of lead strengthened with iron, the thickness of the lead being 6 cm. The total amount of radium used was variable, some of it being used for other purposes, but 4 grams was considered desirable. The radium consisted of eighty equal tubes, each 3 cm. long and filtered by 0·5 mm. platinum. These tubes were held in a brass box in four groups of twenty each. The radium could easily be removed from the main container. The face of the lead container, which carried the aperture for the exit of the radiation, was prolonged by a movable lead localiser, 2 cm. thick. The aperture and sides of the localiser were covered with a sheet of columbia wax 5–6 mm. thick with the object of removing the secondary radiations from the lead. By using different localisers the radium-skin distance could be altered if required.

The whole apparatus, which weighed 150 lb. or more, was suspended as shown in Fig. 70 (*b*). The suspension gave considerable freedom of movement which enabled a variety of positions to be obtained.

The radiation " field " of this unit is shown in Fig. 71. The curves are the usual isodose curves expressed as a percentage of the dose at the centre of the phantom surface to which the apparatus is applied. It is seen that a " cloud " of radiation is suggested rather than a beam, while it is apparent that in view of the large area of the field, the unit would not lend itself easily to an adequate multiple field technique, especially for small lesions in such sites as the larynx and naso-pharynx.

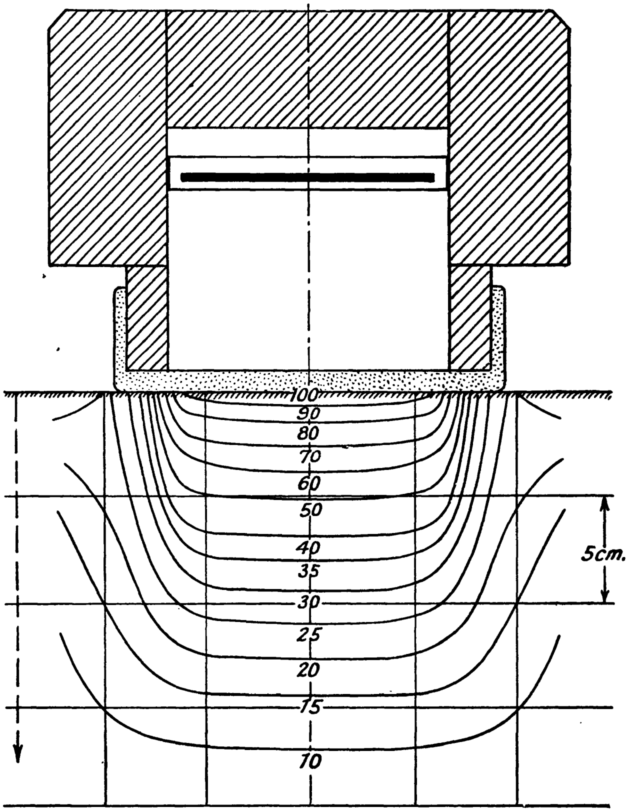


FIG. 71. Radiation field of the early Paris unit. (Bruzau and Foreroux.)

(*b*) AN EARLY WESTMINSTER HOSPITAL UNIT.[5] One of the early radium units used at Westminster Hospital is illustrated in Fig. 72. This apparatus tended towards being a copy of the Paris method in that it used a large aperture, but its use was made more difficult, and possibly less accurate, because the simultaneous treatment of two patients was attempted. For this purpose the container was designed so that two beams emerged, one above and one below. This container could be tilted about one axis only so that practically all adjustments of the unit to the patient had to be made by means of stretchers mounted above and below the container. Each stretcher could be raised, lowered, traversed in either direction, or tilted.

The unit contained 4 grams of radium in twenty tubes of 200 mgm. each which were arranged in four groups of five. Each group could be withdrawn into the walls of the container when not required, so that it was buried in lead of 3 in. minimum thickness. To minimise exposure of personnel, the patients were placed approximately in the required position by means of the dummy apparatus (foreground, Fig. 72). The stretchers were then moved on until the same relative position at the true unit was obtained, when close adjustment was effected. The radium was then pushed back into position by means of the handles outside

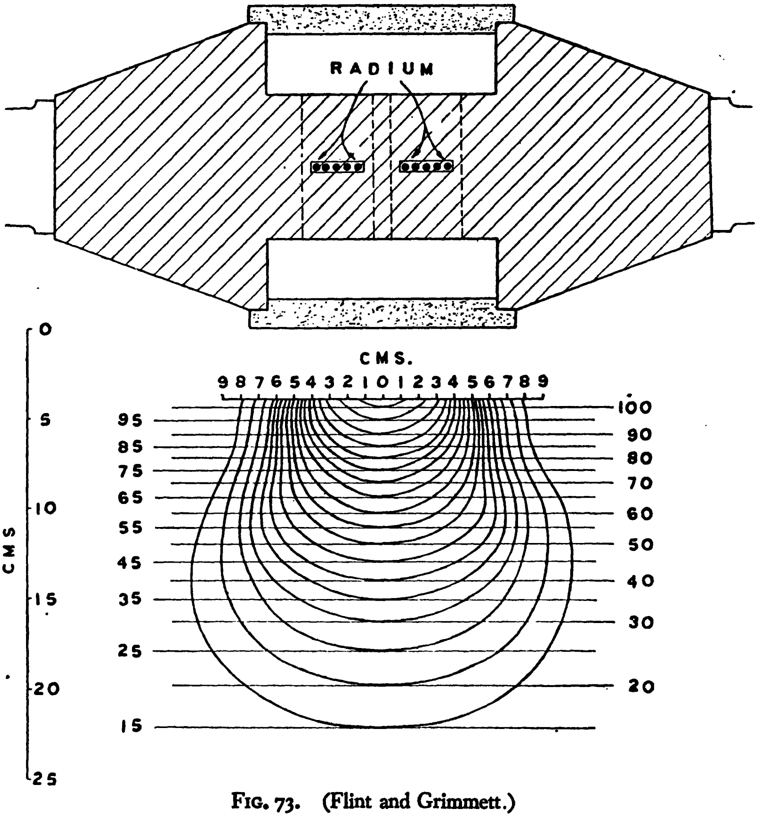


FIG. 73. (Flint and Grimmett.)

the unit. When in use, the four groups of radium sources were approximately at the corners of a 10 cm. square. The total filtration of the gamma radiation was approximately equivalent to 1 mm. of platinum, consisting of monel metal, brass, aluminium, and wood, in that order. The wood was in contact with the patient.

The radiation "field" of the unit, as measured in air,[6] is shown in Fig. 73. As in the case of the Paris unit, the radiation was distributed over such a large area that any "cross-fire" technique, apart from that of opposing fields, was practically impossible.

3. Modern Types of Radium Mass Units

(*a*) THE WESTMINSTER HOSPITAL 4-GRAM UNIT. The radium unit now in use at Westminster Hospital has certain characteristic features which have arisen as a result of continual research and experience with different kinds of mass units during the past thirteen years.[5, 6, 7, 8, 9, 10] In the design of this the object has been to obtain a compact unit with a high degree of flexibility and a sharply defined, narrow radiation field, while adequate protection of personnel is maintained.

The essential features of the apparatus are shown in Fig. 74, which is a photograph of the unit. It consists of two containers for the radium source, only one of which contains the radium at one time. These containers are of equal weight and are suspended from a strong wire-rope cable over a simple pulley system, one container counterbalancing the other. When it is so desired, the system may be braked. The pulley wheels are mounted on an arm which may be rotated so that either container is in the treatment position T, while the other is over the lead safe S. The radium may be changed from one container to the other by the following series of operations, all of which are controlled from a control panel P more than 3 metres away from the unit. The supporting arm is rotated so that the charged container is over the safe S and is then lowered on to the safe. A lift within the safe is driven up within the container by an electric motor, and, after the radium has been released, is lowered again to take the radium down within the safe. A reversal of this procedure with the other container over the safe, transfers the radium into the container. Thus the transference is made with a minimum of exposure to the operator.

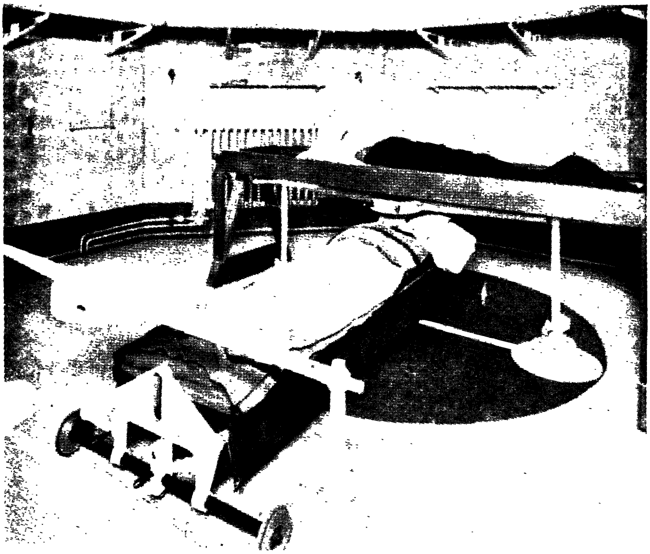


FIG. 72. Early 4-gram unit used at Westminster Hospital.

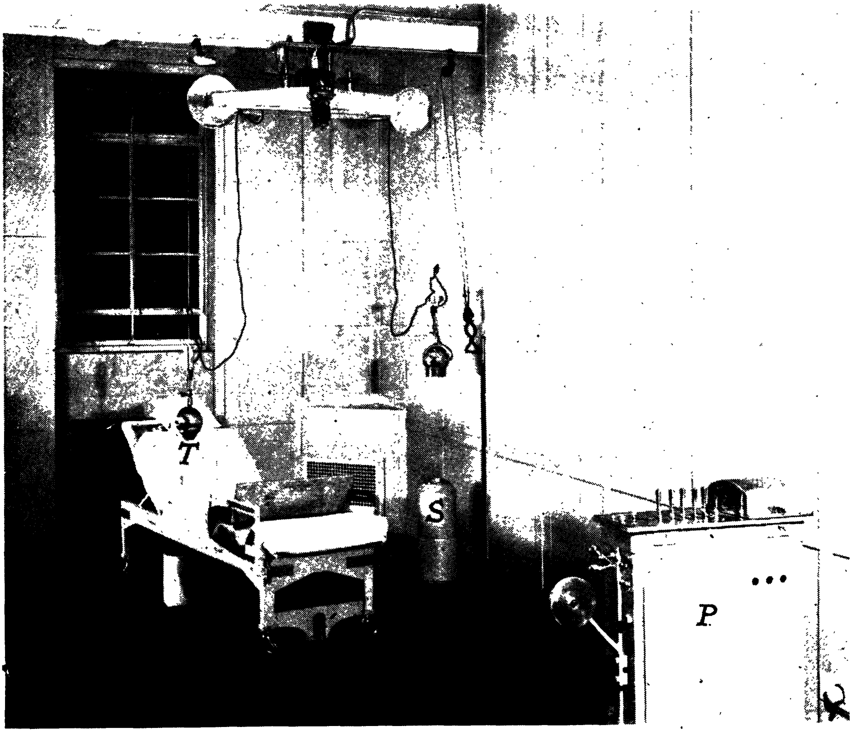


FIG. 74. Westminster Hospital 4-gram unit showing radium containers, suspension, safe and control panel.

Both containers, which are spherical (diameter 16 cm.) except for the aperture, are made of an alloy of tungsten,[11, 12] which has a density of 16·5 gm./c.c., that is, approximately one and a half times

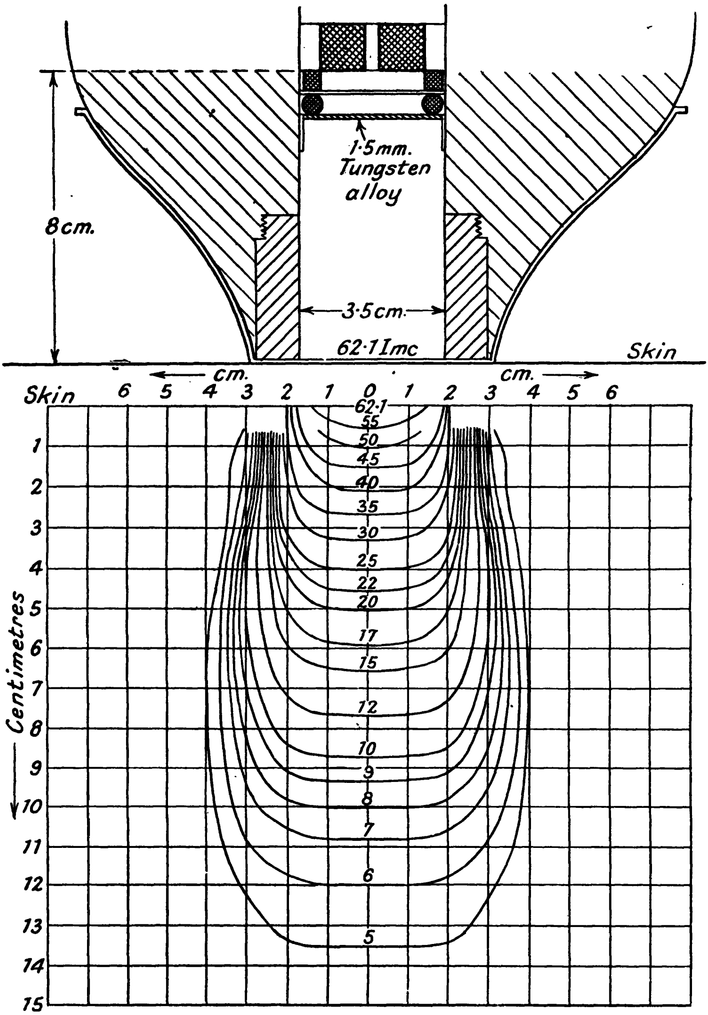


FIG. 75. Radiation field of 4-gram unit (small port); curves of iso-intensity expressed in Imc. Skin intensity = 62·1 Imc ≡ 497 *r*/hour; D_{10} = 13·2 per cent. (Flint and Wilson.)

that of lead. This alloy enables adequate protection to be provided, while the dimensions required are kept much smaller than would be necessary if lead were used. The minimum thickness of alloy around the radium source is 6 cm. One container has an aperture of only 3·5 cm. diameter, the other an aperture of 9 cm. diameter. The smaller of these apertures is defined by a cylindrical collar of platinum 3·5 cm. deep and 1 cm. thick (see Fig. 75). This collar is included in order to obtain a very sharp " cut-off " of radiation at the edges of the beam, while keeping the overall dimensions of the aperture quite small. This feature is an advantage in the application of the container to sites in the neighbourhood of a patient's neck. The larger aperture has tungsten alloy boundaries and gives a much wider field of radiation for the treatment of more extensive lesions. The weight of each container, which can be easily and freely moved in all directions, is approximately 65 lb.

The total quantity of radium within the unit is 4 grams, made up as follows. There are two cubical units each containing 1 gram, with walls of monel metal of 1 cm. side and 0·5 mm. thickness; four tubes containing 250 mgm. each of which are 16 mm. long and of square section 5 × 5 mm., and five tubes containing 200 mgm. each of which are 14 mm. long and 4·6 mm. in diameter. All these tubes have walls of monel metal 0·3 mm. thick. The way in which all these sources are mounted relative to one another is indicated in Fig. 75. Attempts were made to influence the shape of the resulting radiation " field " by the character of this mounting, but it was found that for such close packing as the small aperture necessitates and with the radium-skin distance of 8·0 cm. that is used, the source behaved almost as a point source regardless of the actual distribution. It is seen also that in the arrangement of such a large source within such a small compass, a considerable amount of self-screening is unavoidable. Indeed, it would appear that if even larger sources are to be used in the future along with small ports of entry, the suitable concentration of the radium is a question that will require considerable attention. The main filtration of the radiation is provided by a plate of tungsten alloy 1·5 mm. thick, situated immediately below the source. In application to the patient, the aperture of the unit is covered by a secondary filter of brass sheet 1 mm. thick. This absorbs the secondary beta radiations from the heavy metals of the containers and itself gives rise to only a minimum of such radiations. The total filtration of the gamma radiation is equivalent to 1·93 mm. of platinum.

The characters of the radiation "fields" produced by the apparatus are illustrated by the systems of isodose curves shown in Figs. 75 and 76. The curves show the distributions of intensity throughout a water phantom (a celluloid tank filled with water) when the unit is applied to one surface of the phantom. The

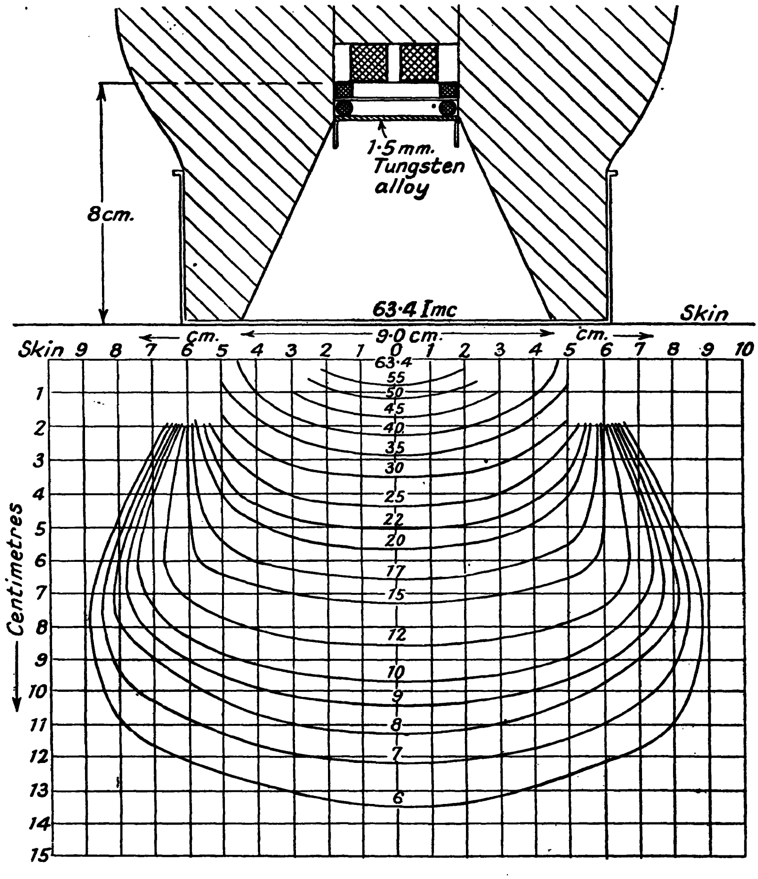


FIG. 76. Radiation field of 4-gram unit (large port); curves of iso-intensity expressed in Imc. Skin intensity = 63·4 Imc. = 507 r/hour; D_{10} = 14·9 per cent. (Flint and Wilson.)

measurements were made [9] with spherical condenser chambers of "Aerion" and the curves are lines of equal intensity expressed in Imc. Fig. 75 is the radiation distribution for the small aperture and the efficiency of the platinum collar in producing a sharp "cut-off" of radiation is apparent. The emergent radiation has much more the character of a beam than that of the earlier units. The distribution for the larger aperture is shown in Fig. 76. Because of the extra scattered radiation arising from the greater bulk of irradiated medium, the doses at a depth in this case are a slightly higher percentage of the surface dose than for the smaller aperture.

It was originally arranged that the beam was directed to the treated site by means of cups which were suitably attached to the patient. The radium container was then held fixed in the cup by spring catches mounted on the side of the container. With the development of newer methods of approach, which we shall discuss later, this method of directioning is now seldom used.

(*b*) THE RADIUM BEAM THERAPY RESEARCH 5-GRAM UNIT.*[13] This unit has many features in common with those of an apparatus developed at Radiumhemmet, Stockholm,[3] but also incorporates an entirely new and extremely valuable feature. The apparatus is provided with an arrangement for pneumatic introduction of the radium into the unit from a storage safe and *vice-versa.* This device enables one to spend much more time adjusting and directioning the unit to the patient, since no exposure of personnel is involved. The radium is blown into the unit by air pressure, *after* the apparatus has been adjusted and all personnel are removed to a safe distance.

Fig. 77 shows the radium container, storage safe and flexible inter-communicating pipe which together form the complete apparatus and the container itself is shown in more detail in Fig. 78. The container is counterbalanced and is mounted on ball-bearings in a trunnion fixed to a vertical shaft hanging from the ceiling. By means of gearwheels the apparatus can be raised or lowered as a whole and the container may be rotated about its axis in the trunnion. The main body and aperture of the unit are made of tungsten alloy, the rest chiefly of lead. Interchangeable nozzles are fitted to the aperture so that it is possible easily to change the size and shape of the radiation " field " as well as the focus-skin distance.

The radium source, 5 grams in all, is made up of twenty-five monel metal cylinders, 12·8 mm. long and 5 mm. in diameter with walls 0·5 mm. thick. Each tube contains 200 mgm. of radium element. The tubes are packed within a steel bobbin (as in Fig. 79)

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* At the present time this same unit is charged with 10 grams of radium.

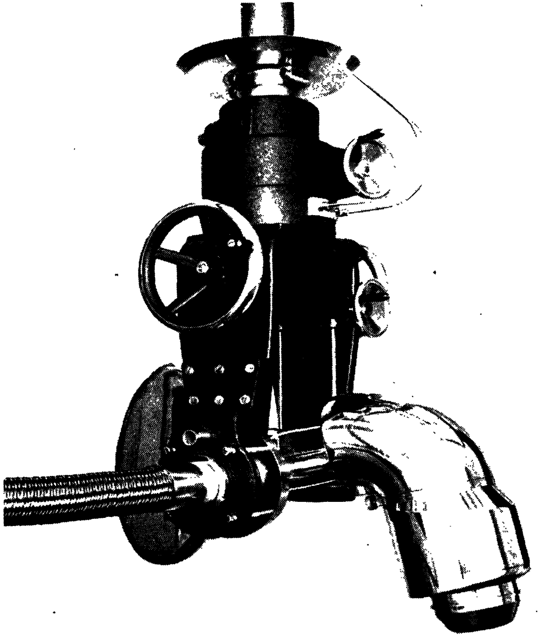


FIG. 78. Container of 5-gram unit of Radium Beam Therapy Research (M.R.C. Radiotherapeutic Research Unit, formerly Radium Beam Therapy Research).

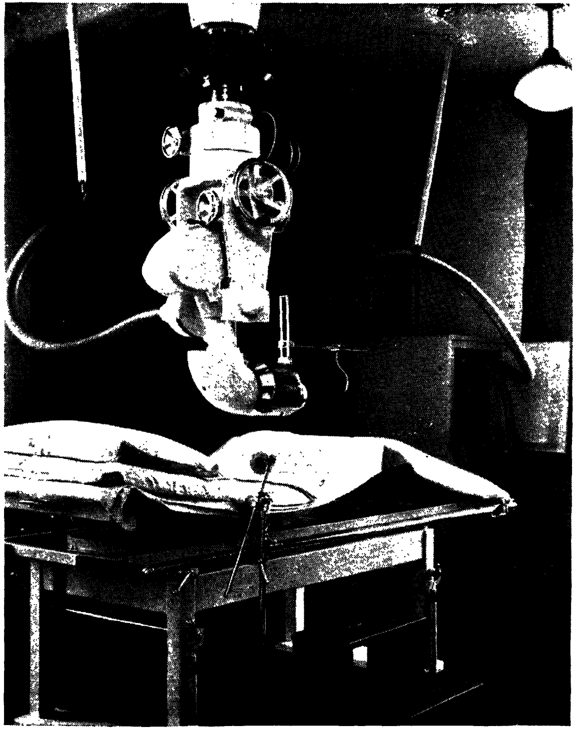


FIG. 77. 5-gram unit of Radium Beam Therapy Research showing container, safe and interconnecting pipe for pneumatic transference of the radium (M.R.C. Radiotherapeutic Research Unit, formerly Radium Beam Therapy Research).

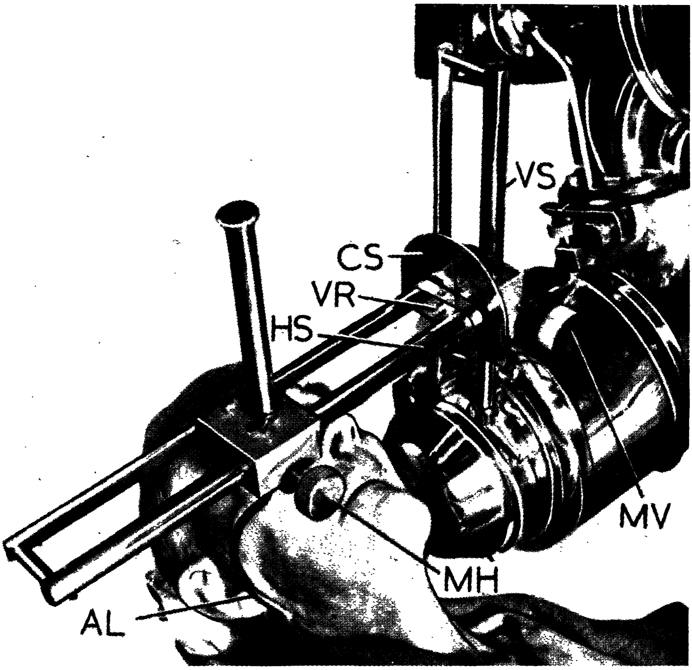


FIG. 80. Directional caliper used with the Radium Beam Therapy Research Unit for accurate localisation of the beam and estimation of tissue dosage. (Green.)

so designed that it can be blown or sucked by air pressure from the storage safe, along the pipe to the container, or *vice-versa.* The total filtration of the radiation is equivalent to 1·8 mm. platinum.

Fig. 79 shows one of the radiation " fields "[14] of the unit (radium-skin distance 8·3 cm., aperture 5 cm. diameter). This is very similar to those of the Westminster Hospital unit, although the " cut-off " at the edge of the beam is not so sharp as for the smaller aperture of that unit. The "field" was determined in this case by means of elektron metal condenser chambers and the dose values are based upon a relation of one Sievert unit equivalent to 9·16 *r*/hr.

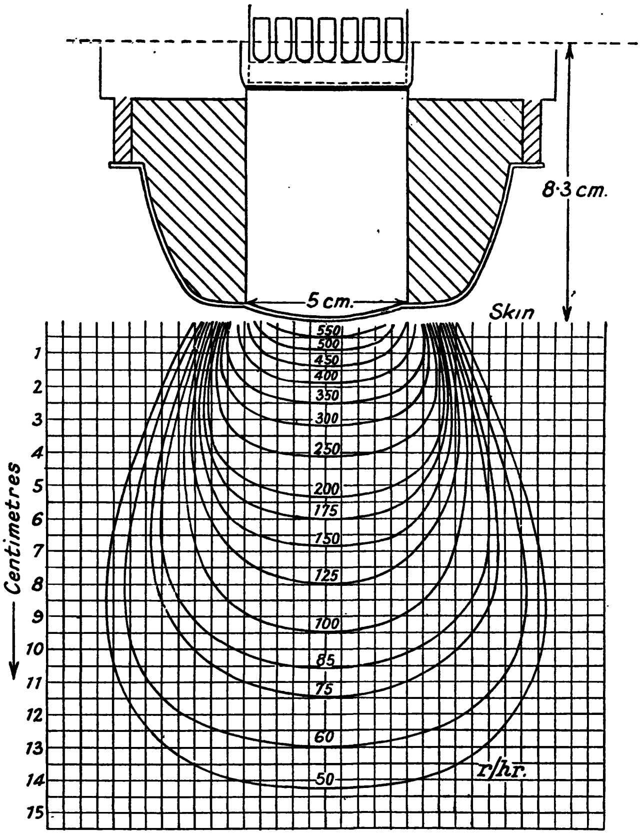


FIG. 79. Radiation field of Radium Beam Therapy Research unit. (Wright.)

In the application of this unit to the patient, very special attention has been given to the accurate positioning and directioning of the beam and to the maintenance of the patient in the required position throughout the treatment period; this is usually of the order of an hour. For the purpose of accurate directioning a calliper has been described by Green[15] which may also be used for the estimation of dosage. This is illustrated in Fig. 80, where it is shown attached to the unit which is at the same time applied to the patient. The latter is kept in position throughout the treatment by means of a head stabilising device consisting of a number of pressure clamps which prevent the likely movements.[16]

4. Dosage in Teletherapy—Determining Factors

It has been seen that to a certain extent, it is possible to influence the radiation distribution from a mass unit by the design of the radium container. There are, however, a number of other physical factors which play an important rôle in determining the therapeutic efficiency of the unit. The essential problem in radium teletherapy is identical with that of deep X-ray therapy, namely, to deliver at a depth in tissue, as great a percentage as possible of the dose received by the skin surface to which the unit is applied. The several factors which determine the magnitude of this "percentage depth dose" (written as D_d for a depth d cm.) are similar to those of deep X-ray therapy, but different in degree. These factors are (i) the focus-skin distance, (ii) filtration and (iii) scatter and absorption; the last, of course, depends upon the area of the field irradiated.

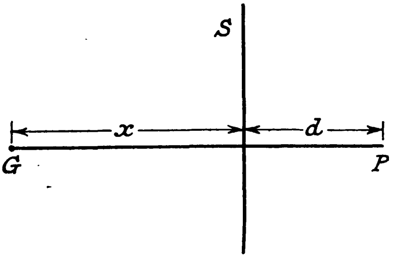


FIG. 81.

(i) *Focus-skin Distance and the Inverse Square Law.* The most important factor affecting the percentage dose at a depth from a radium unit is the distance between the radium "focus" and the skin surface to which the unit is applied. This is because, in common with other similar radiations, the intensity of gamma radiation depends upon the inverse square law. Thus suppose, as in Fig. 81, a source of G grams of radium is at a distance x cm. from the skin surface and we are concerned with the percentage depth dose at a depth d cm. below the surface. Neglecting any other factors for the moment,

$$\text{The intensity at the surface } S = \frac{G}{x^2}$$

$$\text{and the intensity at the point } P = \frac{G}{(x+d)^2}$$

$\therefore$ the intensity at P is a fraction of that at S equal to :

$$\frac{x^2}{(x+d)^2} \times 100\% \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If d is given a fixed value, say 10 cm., we may examine how the percentage depth dose at this depth (D_{10}) depends upon the value of the radium-skin distance as shown in Table 23.

TABLE 23.—*Variation of Percentage Depth Dose D_{10} with Radium-skin Distance*

RADIUM-SKIN DISTANCE x in cm.	5	10	15	20	30	40
PERCENTAGE DEPTH DOSE D_{10}	11·1	25·0	36·0	44·4	56·2	64·0

From this table it is seen that the percentage depth dose increases with the increase in radium-skin distance; very markedly so for the smaller distances. It is thus a distinct advantage to use as great a radium-skin distance as is compatible with the other considerations such as effective dosage-rate, etc. The values of Table 23 neglect the other effects of absorption, etc., which are present in actual practice, but the tendencies indicated by them are correct. Thus the variations of percentage depth dose for an actual radium unit, when the radium-skin distance is varied within the limits most commonly met with in practice, have been examined by Flint and Wilson[8]; their results are shown in Fig. 82. The curve given shows how the measured value of D_{10} for a 2-gram radium unit depended upon the radium-skin distance.

In practice the radium-skin distance cannot exceed a value which depends upon the quantity of radium available, since it is essential that the absolute value of the dosage-rate be kept sufficiently high in order (*a*) that the radiation will produce satisfactory biological reactions and (*b*) that the treatment may be completed within a reasonable and suitable time. Conditions actually used in three different institutes, viz.: the Radiumhemmett, Stockholm, The Radium Beam Therapy Research, and Westminster Hospital, are set out in Table 24. From this it may be seen that with quantities of radium between 2 and 5 grams, the radium-skin distances used range only from 5 to about 8 cm. and the dosage conditions are very similar.

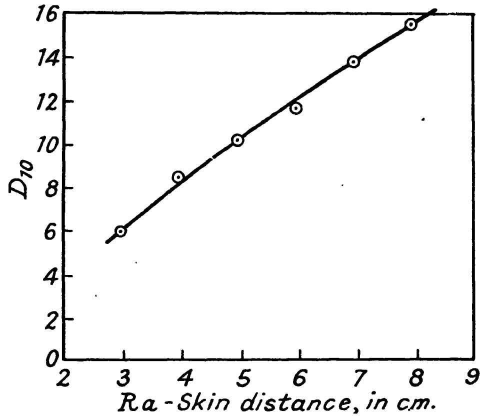


FIG. 82. Relation between percentage depth dose and radium-skin distance. (*Flint and Wilson.*)

TABLE 24.—*Physical Details of Teletherapy Units at Various Institutions*

Institution	Quantity of radium	Radium-skin distance	Diameter of Field	Skin-dosage rate	Dosage rate at 5 cm. depth	Dosage rate at 10 cm. depth	Percentage depth dose D_5	Percentage depth dose D_{10}
	gm.	cm.	cm.	r/hr.	r/hr.	r/hr.	per cent.	per cent.
Westminster Hospital	2·0	5·3	3·5	530·0	135·0	52·0	25·5	9·8
	4·0	8·0	3·5	497·0	160·0	65·7	32·2	13·2
	4·0	8·0	9·0	507·0	176·0	75·4	34·7	14·9
Radium Beam Therapy Research	4·9	6·4	5·0	775·0	220·0	94·5	28·4	12·2
	4·9	8·2	5·0	485·0	180·0	73·0	37·2	15·1
	5·0	8·3	5·0	630·0	210·0	92·5	33·3	14·7
	5·0	8·3	8·0	630·0	230·0	104·0	36·6	16·5
Radiumhemmett	3·05	6·2	8·0	465·0	151·0	69·8	32·5	15·0

(ii) *Filtration.* It has been a tendency to use fairly heavy filtrations in the construction of radium mass units, the intention being to use only the very hardest of the gamma radiation in order to obtain the maximum possible penetration. As a result of a general investigation into the factors affecting depth dose, Mayneord and Honeyburne[17] showed that increase in filtration beyond 0·5 mm. of lead + 0·6 mm. brass produces no appreciable improvement in depth dose. A heavy filter may therefore be a disadvantage, since it will absorb useful radiation.

(iii) *Absorption and Scatter.* The percentage depth dose at any point depends upon the "back-scatter" at the surface, the absorption in the medium and the radiation scattered to the point from the surrounding medium. In the case of X-ray therapy, these factors, especially the latter, are of a considerable magnitude. In radium teletherapy the same factors affect the result, but in a very different degree. As we have seen already (Chap. II) the penetration of gamma radiation is much greater than that of X-radiation, but the amounts of scattered radiation are very much smaller. The many measurements that have been published show, for instance, that even for quite large fields, the surface "back-scatter" does not amount to more than 5 per cent. of the total radiation, while for small fields, it is negligible.

We have seen also (Chap. II) that when a beam of gamma radiation is considered, as distinct from an open source buried within the medium, the scattered radiation does not quite compensate for the absorption by the medium, so that a small effective absorption occurs. Mayneord and Honeyburne[17] have shown that the available data may be interpreted satisfactorily by assuming an "apparent" linear absorption coefficient μ' for water $= 0{\cdot}025$ cm.$^{-1}$.

It might be expected that the area covered by the radium source will affect the amount of scattered radiation and so affect the depth dose. It appears, however,[17] that this is not so for radium-skin distances of the order of 10 cm. or more, although for small distances (2–3 cm.), increase in the area of the source may produce a marked increase in depth dose. The gain in percentage depth dose that results from an increase in the size of the field is clearly seen by reference to the values given in Table 24 for fields of different sizes in which the radium-skin distance is the same.

5. Calculation of Depth Doses

By a combination of the inverse square law (Equn. 1) and the apparent absorption of a gamma-ray beam, the percentage depth dose D_d at any depth d in a tissue-like medium (water) may be written as :—

$$D_d = \left(\frac{x}{x+d}\right)^2 . e^{-\mu' d} . \times 100 \quad . \quad . \quad . \quad . \quad (2)$$

Thus, to a first approximation, it is possible to calculate the depth doses that should result from a beam of gamma rays provided by a

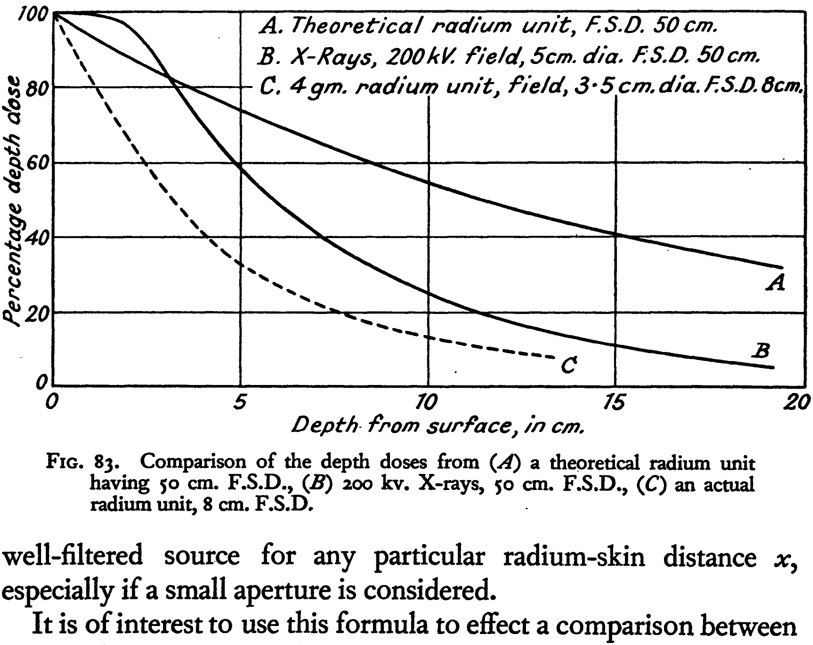


FIG. 83. Comparison of the depth doses from (*A*) a theoretical radium unit having 50 cm. F.S.D., (*B*) 200 kv. X-rays, 50 cm. F.S.D., (*C*) an actual radium unit, 8 cm. F.S.D.

well-filtered source for any particular radium-skin distance x, especially if a small aperture is considered.

It is of interest to use this formula to effect a comparison between the depth doses provided by 200 kv. X-radiation and radium at an equal focus-skin distance. Fig. 83 shows the measured depth doses of 200 kv. radiation[18] (Villard circuit, field 5 cm. diameter, Thoræus filter) for 50 cm. focus-skin distance and also the depth doses calculated for a hypothetical radium unit utilising the same focus-skin distance. Such a unit is impracticable because it would require more than 150 grams of radium to provide an adequate dosage-rate, but its consideration is of considerable interest in view of the present attempts to achieve "equivalent gamma radiation" by the use of higher generating potentials. It is apparent that such a unit, or its equivalent, gives a very much increased depth dose at the greater depths as a result of the greater penetration of the radiation. With the small focus-skin distances used in teletherapy at present because of the relatively small quantities of radium available, this penetration is not so obvious. Thus the broken curve C of Fig. 83 represents the depth doses for the present Westminster Hospital 4 gram unit (field 3·5 cm. diameter) in which the focus-skin distance is only 8·0 cm. Comparison of the curves A and C reveals the gain that would be achieved if the large distance could be used.

6. Measurement of Depth Doses

In making the measurements of depth doses that have been published from time to time[4, 8, 9, 10, 14, 17, 19] (see Figs. 75, 76, 79), ionization chambers constructed of a variety of light atom materials have been used. Some of these, such as aluminium, have an atomic number considerably different from that of air, and this difference may be an important factor in the measurement of depth doses where scattered radiations of increased wave-length may be present.

In this connection Zimmer has suggested[20] that the published measurements made with elektron metal ionization chambers are not so accurate as those made with more strictly air-wall chambers built of materials such as " Aerion " or celluloid. Rann,[19] however, made comparative measurements with chambers of celluloid and elektron metal at different depths in a water phantom, and his results suggest that elektron metal chambers do give true comparative readings of depth doses. This is supported by the results obtained by Wilson [21] (see Chap. II), which suggested that the maximum effective wave-length of the radiations comprising the depth dose of a radium unit is of the order of 31 X.U. For wave-lengths up to this value, the ionization within an elektron metal chamber is theoretically the same as in one of graphite to within 1 or 2 per cent., which is of the order of the experimental error in such measurements.

7. Application of Physical Data to Clinical Work

As a result of the vast amount of radio-biological and clinical research that has been done, it is known that a number of physical factors are of the utmost importance in determining the biological reaction in radiation therapy, although in many cases, the attention paid to these factors is still insufficient. The factors are :—

(1) The dose of radiation delivered, (*a*) at each individual

treatment, if the total treatment is fractionated as is usually the case, and (*b*) the total for the whole treatment.

(2) The dosage-rate or dosage-rates at which the radiation is delivered.

(3) The time in which each dose is given.

(4) The time interval between each dose.

(5) The total overall time of delivery of the whole dose.

In practice, these dosage factors, as they apply for the skin portals, will of necessity be of great interest, since the skin reaction may ultimately determine the total time of treatment. But those for the lesion itself, or other sites carrying the disease, are of the greatest importance also, and should be recorded always. To collect tissue-dosage data of this type would seem an obvious requirement if the reaction of a tumour is to be related at all to the physical factors of the therapy. It is remarkable, however, how often in radiation therapy, this essential data is still omitted, while full details of skin dosage is given.

8. Determination of " Tissue " Dose in Clinical Practice

(1) *Direct Measurements of Dosage-rate.* Obviously, if the dosage-rate and treatment time are known, it is a simple matter to determine the dose given. When the site concerned is suitably accessible the dosage-rate may be determined by means of measurements made directly at the site with condenser chambers. Thus Fig. 84 illustrates a measurement being made on the tongue during treatment; the ionization chamber is carefully protected from direct contact with the moist tissues by a thin rubber sheath.

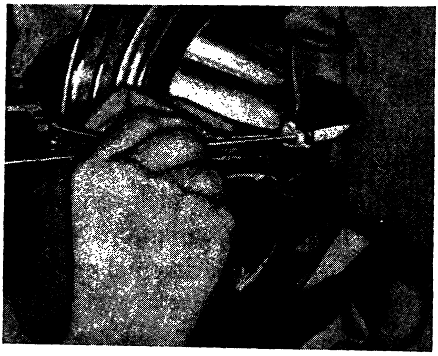


FIG. 84. Direct measurement being made upon a tongue by condenser chambers during teleradium treatment. (*Sievert.*)

Two disadvantages of this method are (*a*) it is limited to those sites to which access may be obtained, and (*b*) it involves considerable exposure of the personnel making the measurements.

(2) *Interpolation of Dosage-rate from Dose-contours.* In practice it is more convenient to use the known radiation distribution for the unit as measured in a phantom (*e.g.*, Figs. 75, 76 and 79) and to locate the tissue site with respect to this. This approach is justified by the fact that measurements made in a water phantom are practically identical to those measured in cadaver tissues.[21] This result, which is to be expected theoretically, has been further confirmed by the comparison of a large number of direct measurements made in patients, with the values obtained by interpolation in the dose-contours.

In this method it is essential that the site at which the dosage is to be found may be accurately defined with respect to the ports of entry of the beams. The position of the site within each radiation field is then known, so that the dosage-rate at the site due to each field may be determined from the dose-contours. In the case of accessible sites, the position within the radiation field may be determined with precision by means of a calliper such as that already mentioned[15] (Fig. 80, facing p. 169). The pointer of the calliper is made to coincide with the site being considered, while the radium unit is applied to the patient in the treatment position, and from the scale readings of the various calliper movements, the position of the site within the radiation field is determined.

In the case of inaccessible sites, various methods are adopted which involve the use of measurements of the patient's anatomy, radiographs, and the application of scale models and cross-sectional anatomical diagrams. These methods are not so precise as the calliper, but give a fair degree of accuracy.

9. Three-dimensional Dosage Distribution

In the treatment of cancer by radium teletherapy, the object in view is the delivery of an adequate and homogeneous radiation to the diseased tissues. Further, it is desirable that the amount of radiation received by the diseased tissues is as high a fraction as possible of that received by the normal tissues, which are of necessity irradiated. Planning the arrangement and direction of the ports of entry, so that the resulting distribution of radiation within the tissues most nearly fulfils these conditions, should, therefore, be one of the main features of radium teletherapy (and deep X-ray) technique. From the physical aspect, and the problem is almost entirely of a physical nature, it becomes necessary to examine the possibilities of methods whereby the three-dimensional distribution of radiation, due to combined multiple ports of entry, may be investigated and controlled. It is only within recent years that such methods have been devised so that comparatively little general use has been made of them so far, at least in clinical practice.

(1) *Determination of Dosage at Key Points.* An approximation to a complete determination of the dosage distribution throughout the irradiated volume of tissue may be made by taking readings, by one means or another, at a number of key points in the volume, of the dosage contributed by each beam of radiation.[16] By summation of these separate values, the total dose in röntgens is determined at each point. In certain instances, by modifying the position and direction of one or more of the beams, or by varying the total irradiation time through the different ports of entry, it is possible to adjust the dosage values at the key points so as to give a good degree of homogeneity, *i.e.*, a close equivalence between the dosage received at the different points. The latter method of adjustment has the disadvantage, that the total amount of radiation that can be delivered through one or more of the fields, may be limited for physical reasons, in cases where it may be necessary to deliver the very maximum quantity of radiation that is biologically permissible.

(2) *Complete Spatial Distribution of Dosage.* Considerable attention has been given recently to methods, suitable for both X-ray therapy and radium teletherapy, whereby it is possible to determine the complete three-dimensional radiation distribution produced by any combination of a number of specified X-ray or gamma-ray beams; specified, that is to say, in the sense that the dose-contours of the beams are known in a principal plane.

(*a*) DOSE-CONTOUR PROJECTION. In the case of a number of co-planor beams, two-dimensional distributions may be studied by the superposition and summation of the principal plane dose-contours of the individual beams in their correct relative positions. Provided it is possible to determine the corresponding dose-contour chart for any plane section through the beam of radiation, this same method may be extended to a number of planes throughout the irradiated volume, so that the complete spatial distribution may be arrived at, whatever the directions of the individual beams. To this end, methods have been described, whereby, in the case of beams of circular cross-section, the dose-contour charts in any plane through the radiation beam, may be projected from the known dose contours of the principal plane.

Mayneord does this projection[22] by means of a simple, but ingenious, apparatus, which he calls a " dose-contour projector." Fig. 85 shows an apparatus of this kind. The use of the apparatus is dependent upon the fact that when the dose-contour diagram for the principal plane (*i.e.*, a plane containing the central ray) is rotated about the axis AB, the contours cut out in space, complex solids whose surfaces are isodose surfaces. Thus the problem of drawing the contours in any plane, is the determination of the shapes of the sections of the isodose surfaces cut by the plane. Such sections are obtained by means of the apparatus, upon a sheet of paper attached to the horizontal drawing board. The sheet of transparent material (" perspex " or glass) carrying the principal plane dose-countors, can be rotated about the axis AB and is set by means of the available adjustments, at the angle to the central axis, and depth from the skin surface, of the plane in which the contours are required. A dose-contour is projected by slowly rotating the sheet from one position to another. In each position, a mark is made upon the drawing paper by means of the marker M, when the pointer is in contact with the dose-contour of the principal plane. When all these individual marks are joined by a smooth curve, the projected contour is obtained. For further information reference should be made to the original work.

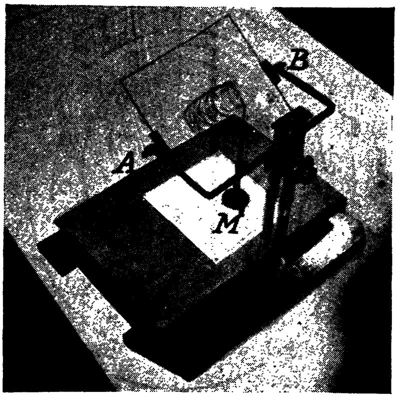


FIG. 85. A dose-contour projector.

The same results may be obtained by means of simple geometrical methods described by Wilson[23] which involve the use of drawing instruments only. These methods, in some instances, are more tedious than that of using the dose-contour projector, but may be of value in hospital departments where it is difficult to obtain the necessary apparatus. Some examples of the results obtained by these methods of projection are shown in Fig. 86. Fig. 86 (*a*) shows the dose-contours for the Westminster Hospital 4-gram unit, 3·5 cm. diameter field, (see Fig. 75) in a plane cutting the principal axis at 60° at a depth of 4 cm. from the surface, and Fig. 85 (*b*) gives the corresponding contours in a plane parallel to the principal plane and 3 cm. from it. The contours are in r/hr.

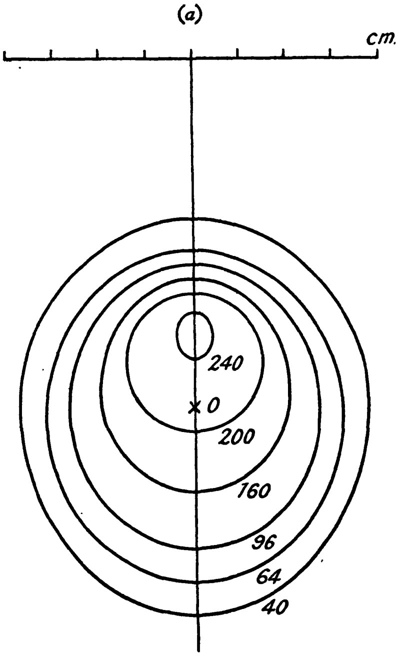


Fig. 86 (*a*). 4 gram unit, field as in Fig. 75. Plane at 60° inclination to axis and at 4 cm. depth.

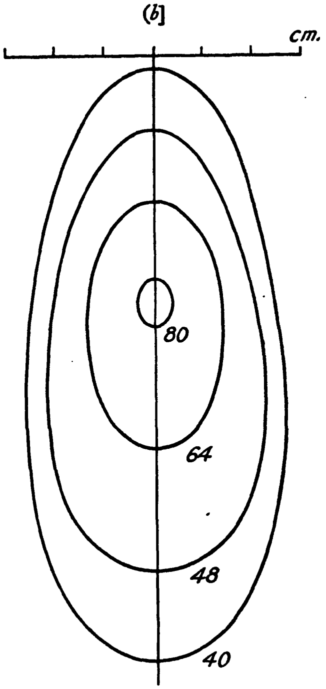


Fig. 86 (*b*). Plane parallel to axis and 3 cm. distant from it.

Another method of obtaining the dose-contours in any section through radiation beams has been described recently by Flanders.[24] In this a thin sheet of light is passed through a model of the isodose surfaces made of open mesh wire gauze. The contours in the plane of the sheet of light are visible and can be photographed or drawn. The method is applicable to both symmetrical and unsymmetrical beams.

(*b*) DOSE-FINDING.[22, 25, 26] An alternative procedure to the projection of complete dose-contours is to devise methods whereby the dose at any point within an irradiated volume of tissue, due to each of the fields applied, may be found. If the dose contribution from each field is found, and the sum of these contributions is taken at a sufficiently large number of points, the complete three-dimensional distribution is determined. It is possible to use the dose-contour projector for this purpose, but alternative methods have been described which are more readily applicable.

In these methods of " dose-finding " the actual treatment conditions are reproduced by the use of models of the anatomical part concerned, and the port of entry of the treatment apparatus (radium unit or X-ray applicator); these are positioned together as were the originals during treatment. A suitable displacement of the anatomical model is made while all else is kept fixed, and the dose-contours (drawn on a sheet of " perspex " or glass) are fitted into the model of the port of entry of the treatment apparatus to correspond to the radiation beam. If, now, some pointer device is available, it may be arranged to point at a spot on the dose-contours, exactly corresponding to the same spot within the anatomical model. The process may be repeated for any number of points and for any number of applied radiation fields.

A dose-finder of this type was first designed by Mayneord [22] and has since been used by him to solve many problems of radiation distribution. Fig. 87 shows an apparatus constructed upon the same principle.[25] Fig. 87 (*a*) shows the apparatus when the models are together in the treatment position, and Fig. 87 (*b*) shows it again when the anatomical model (of the chest wall) has been displaced parallel to the double pointer system. In making the displacement, the anatomical model M, carried on a small table, is moved along the small optical bench O parallel to the pointers AB, a distance equal to the separation of the pointers. By means of the apparatus carrying the pointer system, one pointer may be set to point accurately to any specific point within the anatomical model, while the other pointer indicates on the dose-contours T, the dosage at this spot. Obviously, if the exploration be carried out in one plane only, similar results will be obtained as by the contour-projector.

Another apparatus for the same purpose has been described by Spiers.[26] In this, points are located as the meeting place of two beams of light within the anatomical model, to which a replica of the port of entry has been applied as in the treatment. The anatomical model is then removed by sliding it along a fixed track, but the point remains located. If a diagram of the dose-contours is now introduced into the replica of the port of entry as before, the light pointers indicate the value of the dosage at the point concerned. Other points are studied by returning the anatomical model to its original position and readjusting the light beams.

For radiation beams of circular cross-section, the principal plane dose-contours are sufficient, since any point may be included by rotating the sheet bearing the contours, about the central axis of the beam. The problem is more complex when rectangular fields have to be considered, as is most usual in deep X-ray therapy and fairly common in radium teletherapy. In such cases it has been suggested[22] that a number of dose-contour diagrams should be used, each determined for a different axial plane. In any particular case, the diagram corresponding most nearly to the angle required would be used. The author[25] has mounted the various diagrams together at their appropriate angles to one another so that the dosage values at the points indicated may be interpolated with the same degree of accuracy as one can interpolate the values at points between the dose-contours on a single plane diagram. A typical set of such contours for a rectangular (12 × 6 cm.) X-ray beam is shown in use in Fig. 87. It is necessary to represent only one-half of a rectangular field in this manner, since rotation through 180° gives the other half. Similarly, if the field is square, only one-quarter need be represented; the other quarters are given by rotation through 90°, 180° and 270° respectively. In using such three-dimensional representations of rectangular fields by the method shown in Fig. 87, Mayneord's double-pointer method is incorporated,[22, 25] but the pointer indicating the dosage value within the dose-contours consists of two crossing light beams.

10. Typical Three-dimensional Distributions of Dosage.—Indications for Modified Technique.

Honeyburne[27] has used the above methods to study the volume distribution of radiation in a head and neck for a five-field teleradium technique for the treatment of carcinoma of the floor of the mouth, the fields being (*a*) a submental field, 5 cm. diameter, (*b*) two buccal fields 5 cm. diameter, and (*c*) two submaxillary

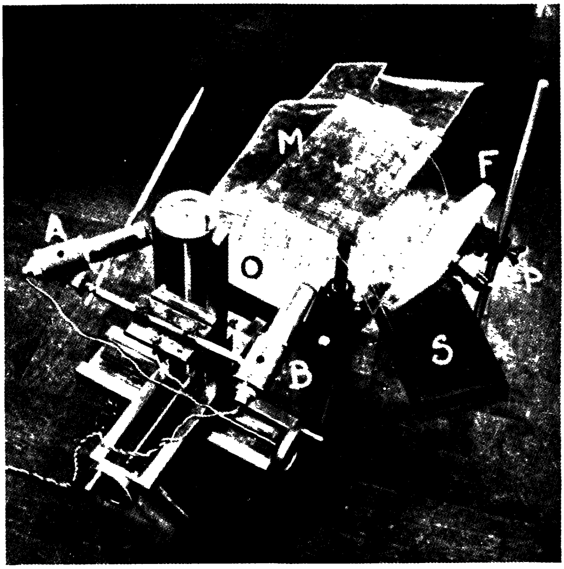


FIG. 87 (*a*). Applicator model applied to anatomical model as for "treatment."

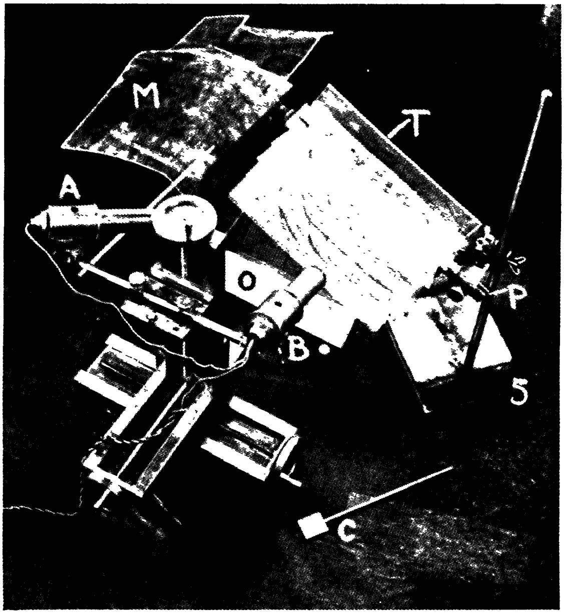


FIG. 87 (*b*). Dose-finding with dose-contours in position. Dose-finder in use with rectangular radiation fields.

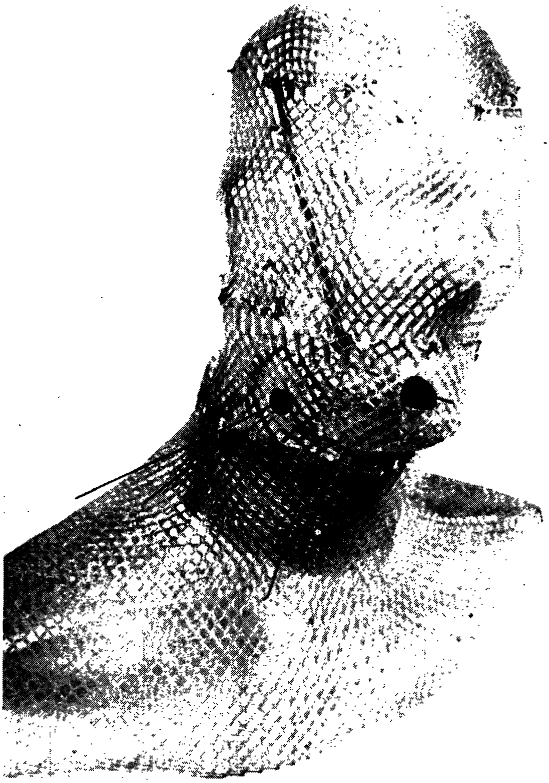
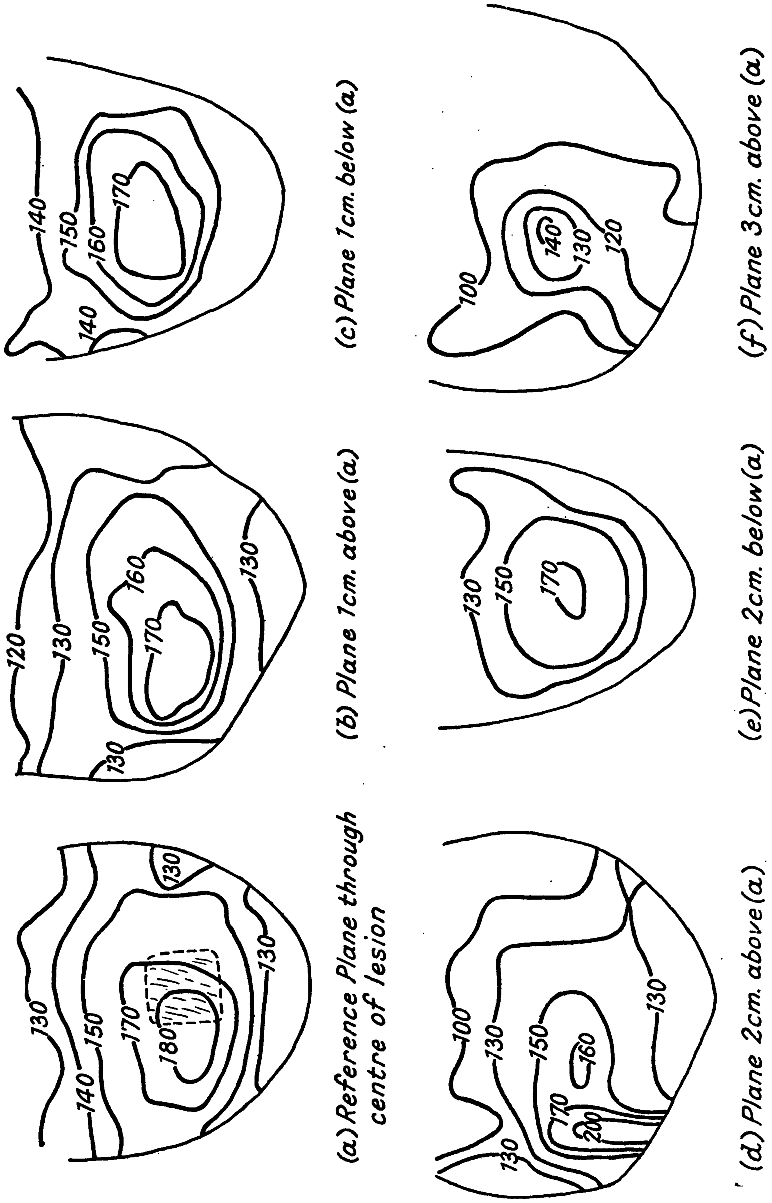


FIG. 89. Illustrating a three-field technique commonly used for irradiation of the right tonsil.



(a) Reference Plane through centre of lesion

(b) Plane 1cm. above (a)

(c) Plane 1cm. below (a)

(d) Plane 2cm. above (a)

(e) Plane 2cm. below (a)

(f) Plane 3cm. above (a)

FIG. 88. Three-dimensional distribution in a head and neck for a five-field teleradium technique (Honeyburne).

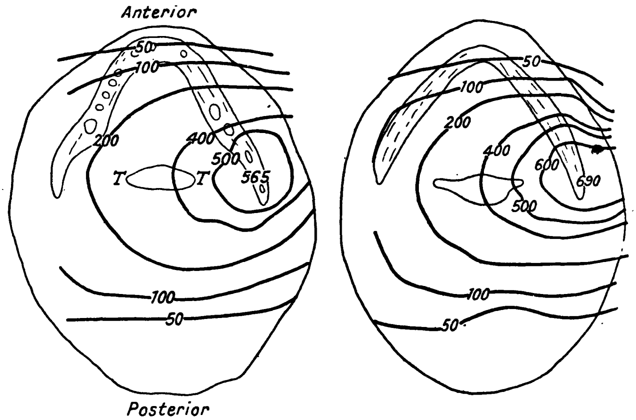
fields, 8 cm. diameter. The results may be presented as in Fig. 88. This shows the total dose-contours in a reference plane and in other planes at fixed distances above and below this plane. The reference plane was chosen to pass through the centre of the lesion.

If the curves are drawn on glass or perspex and the planes are mounted in their correct relative positions, the distribution within the volume of the head and neck may be observed directly.

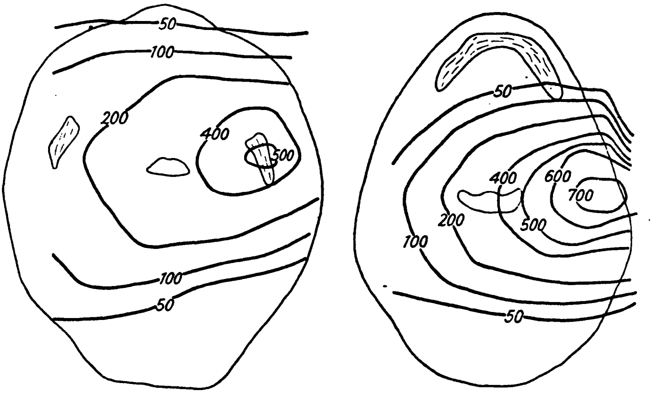
The numbers on the contours state the total dosage obtained for 100 per cent. delivered on the skin at the centre of each of the five fields. These values automatically take into account cross-fire of one field to another, overlap of one field by another, etc. Thus, in considering the resultant distribution so obtained, it must be borne in mind that, other things being, equal the region where any skin reaction will first appear is that region on the skin surface where the highest total dosage is found. This dosage value represents what is usually referred to as the " skin-dose " and the magnitude of the tumour dose must be considered relative to this. Thus, considering the diagrams of Fig. 88, the maximum skin-dose is 200 and nowhere does the tumour dose exceed this, indeed, it is generally below it. It is seen that this arrangement of fields gives less than 100 per cent. of the skin dose to the lesion, and what is more, as Honeyburne[27] has pointed out, the maximum dose does not occur at the site of the lesion as is desirable, but in the region of the mandible.

Similar studies have been made at Westminster Hospital of some of the teleradium techniques which have been commonly used. We may illustrate the type of result obtained by reference to techniques for the irradiation of (*a*) carcinoma of the tonsil and (*b*) intrinsic carcinoma of the larynx.

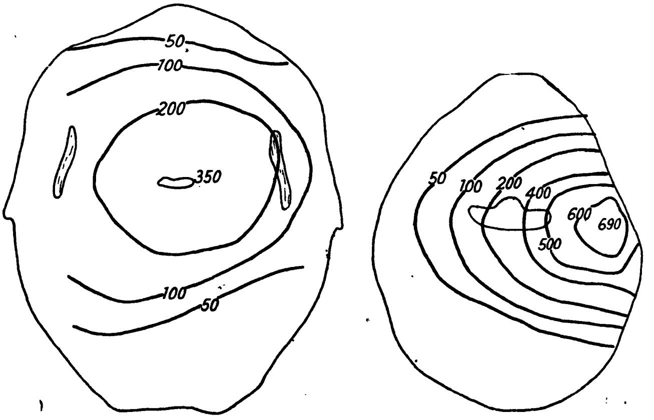
(*a*) A technique that has been used in the treatment of carcinoma of the right tonsil by the Westminster Hospital 4-gram unit is illustrated in Fig. 89. This shows a " nidrose " model of a head and neck with the three fields that are used (each 3·5 cm. diameter) marked upon it. The direction of the beams are indicated by the rods which represent the central axes of the beams, each beam being directed at the tonsil. The volume distribution of radiation found to result from this arrangement is illustrated in Fig. 90, where the total dose-contours are shown for a plane of reference taken through the tonsil and for other planes at various distances above and below the reference plane. The dosage numbers given in this case are the total röntgens for one hour application of each of the fields (see Fig. 75, p. 165), and a few anatomical features are marked in order to make the results more



(a) Reference Plane: through centre of tonsils T *(b) Plane 1cm. below reference plane*



(c) Plane 1cm. above reference plane *(d) Plane 2 cm. below reference plane*



(e) Plane 2cm. above reference plane *(f) Plane 3cm. below reference plane*

FIG. 90.

instructive. It is seen that the maximum dosage (700 *r*) occurs not at the tonsil but below it, and this dosage is received by one region of the skin. Also, the mandible receives a greater dosage than does the tonsil. Indeed, the maximum dosage received by the tonsil is only some 70 per cent. of the maximum skin dosage, and this value falls rapidly at greater depths within the tissues. The tonsil can hardly be considered to be irradiated with the maximum homogeneity and efficiency.

(*b*) In the treatment of intrinsic carcinoma of the larynx by radium teletherapy a common technique is that which uses three fields, left and right laryngeal fields and an anterior field. The anterior field is directed through the anterior commisure so that the beam emerges at the posterior mid-line of the neck; the laryngeal fields have their centres in the same horizontal plane as the anterior field, are closely adjacent to it, and are directed through the posterior ends of the vocal cords (Fig. 91). The total distribution of radiation across the plane containing the central axes of the three fields is shown for an actual case in Fig. 91, each field being as before, that of the Westminster Hospital 4-gram unit, 3·5 cm. diameter. It is hardly necessary to consider other planes in order to bring out the various points concerning the distribution. It may be seen at once that a uniform distribution is not obtained. The dosage is highest in the region of the thyroid cartilage and falls off rapidly towards the posterior of the larynx. In order to deliver an adequate dose to the vocal cords it would therefore probably

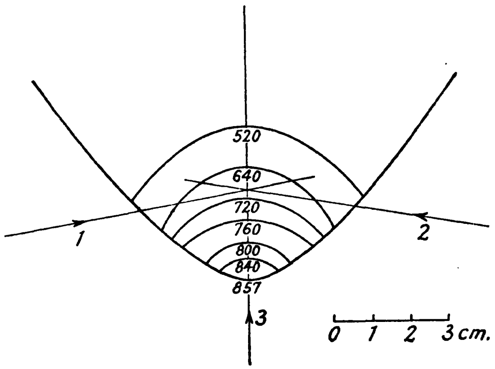


FIG. 91. Distribution of radiation in a common method of irradiating the larynx. The lines 1, 2 and 3 represent the directions of the three beams. Dose values in röntgens.

be necessary to deliver an excessive dose to the thyroid cartilage. Such excessive dosage may run the risk of radio-necrosis.

From these and other cases that it has been possible to consider in detail, it is clear that knowledge of the complete distribution of radiation is of vital importance, and can form a safeguard against local over-dosage. Obviously the ideal would be to determine the arrangement and direction of fields that is required to give the maximum degree of homogeneity along with the maximum possible dosage at the site of the disease. From a study of many other cases, in addition to those described (including many deep X-ray therapy techniques), it appears to the author that the resulting distribution in a combined field technique depends so critically upon the nature of the individual radiation fields, their position and direction, that the ideal cannot always be achieved by a mere arrangement of ports of entry around the external anatomy with the beams directed at the lesion. If a number of cases are treated by what is apparently a common technique of this character, the actual distribution of radiation that results may be quite different in the various cases. It would seem that we have been too apt to regard the beam as a thing of a much simpler character than it really is. If the best possible distributions of radiation are to be obtained, much more attention must be paid to the true shape of the field as represented by its dose-contours.

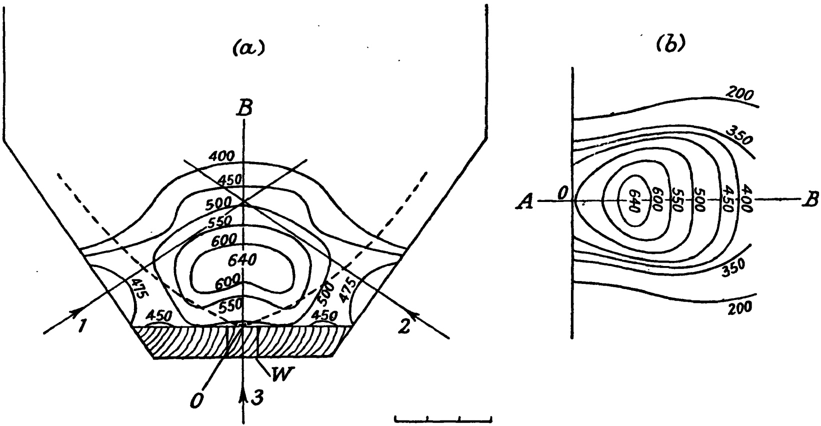
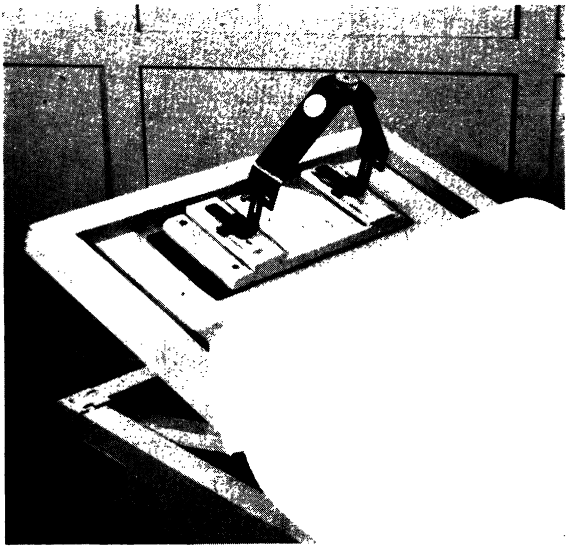


FIG. 92. Pre-arranged uniform distribution of radiation over the larynx. (*a*) In a plane containing all the beam axes. (*b*) Section through the plane *AB* of (*a*) to illustrate degree of volume homogeneity.

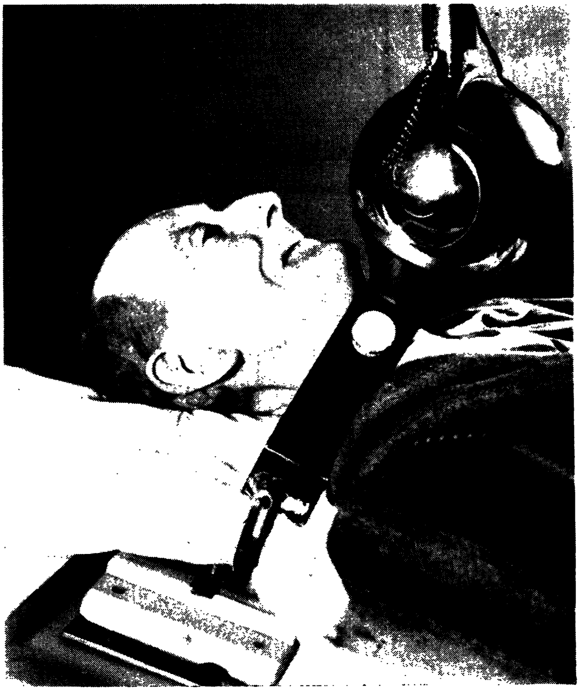
We may illustrate the point by reference to an arrangement of fields described by Flint and Wilson.[28] Fig. 92 (*a*) shows the resultant distribution of radiation that may be obtained by suitable pre-arrangement of beams for the irradiation of intrinsic carcinoma of the larynx. Three fields have been used as in the other technique described above and the section shown is exactly comparable with that of Fig. 91. The directions and positions of the fields in this case are indicated by the lines 1, 2 and 3, representing the axes of the beams; these have been adjusted deliberately to give the homogeneity seen to exist over the laryngeal region. It is important to note that the beams cross at a point which does not necessarily bear any direct relation to the lesion itself. The point (or points) at which the beams are directed is determined mainly by the character of the radiation field.

It would appear that if the optimum arrangement of fields is to be used in every case, it is necessary to decide upon the required arrangement by considering each case in absolute detail before treatment commences. Obviously such a process would involve so much time and labour as to be almost unworkable in practice. To overcome this difficulty it has been suggested[28] that one may develop methods of applying the radiation fields which would be independent of anatomical variations to a large extent. Thus Flint and Wilson[28] have put forward the idea of constructing suitable frameworks or " jigs " which automatically provide for those positions and directions of the ports of entry which give a desired degree of homogeneity of radiation within the framework. In practice these frameworks may conform fairly closely to the part of the anatomy which is placed within the framework so that the lesion lies in the most suitable part of the " field." The general principle is to place the patient within a known " field " in contradistinction to forming an unknown " field " within the patient. Much has yet to be done to develop such procedures for all types of case, but the method is being developed for the simpler types. We may illustrate the procedure by reference to its use for the application of the fields just described to the homogeneous irradiation of the larynx (Fig. 92).

Fig. 93 (*a*) shows the framework which is set up around the neck of the patient and automatically determines the position and direction of the beams as is shown in Fig. 93 (*b*). The brass of which the



(*a*) The jig before the patient is set up for treatment.



(*b*) Patient within jig and radium unit applied.

FIG. 93. "Jig" for automatic positioning and directing of fields designed to produce homogeneous irradiation over the larynx.

[*Facing p.* 188.

apparatus is made serves as the secondary filter of the radium unit. Ideally, no air gaps should be left between the framework and the neck so that the scatter and absorption conditions correspond as closely as possible to those under which the radiation field was determined. In the case of radium teletherapy, however, such gaps are not of great importance, but they would be in an adaptation of the method to deep X-ray therapy. However, by suitable packing, with, say rice bags, it is possible to approach the ideal conditions more closely, and in order to ensure in advance that a fairly close fit is obtained, experience suggests that two or three sizes of framework may be used for each type of case.

It is obvious that if all the ports of entry could be applied simultaneously, the uniform field of radiation would exist continuously throughout treatment and the whole of the tumour bearing region would be irradiated by a definite and equal dosage-rate, so that small movements of the patient during treatment would be almost immaterial. Physically and biologically this would seem to be the ideal method of irradiation, but it is impossible in the present circumstances. As a close approximation to this, however, it would appear to be advisable to irradiate through each port of entry at each individual treatment in preference to the common procedure of treating only one field at a time. In the latter method the lesion does not receive the radiation at a uniform dosage-rate, although it may be dosed uniformly. Of course, modifications in the time of irradiation through each field would have to be made if all fields wer e treated at each period of treatment.

At the present time it is possible only to outline the basic ideas of this kind of approach, but it is felt that the method has much to recommend it, especially for radium teletherapy at its present stage of development, when it is in the most part used for the irradiation of more or less definite sites in the head and neck.[29] * Advantages inherent in this kind of technique are :—

(1) The degree of homogeneity of the radiation throughout the

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* It should be pointed out that in a recent discussion on "The Technique of Radium Treatment of Intrinsic Cancer of the Larynx" Lederman and Mayneord (*British Journal Rad.*, Vol. 16, 1943, p. 301) adopt a rather different attitude from that taken above. Recognising the same fundamental points with regard to the formation of "hot-spots" and the close attention that must be given to the total distributions arising from a number of compounded beams, they set out to control the "hot spot" rather than to provide homogeneity. Their point of view may be expressed most readily in their own words :—

"Homogeneity of field of radiation is, within limits, of relatively minor importance in diseased tissues is improved. The physical conditions are made most definite and accurate control of dosage is possible.

(2) It may be ensured in advance that all the diseased tissues receive adequate irradiation.

(3) Accurate comparison of a number of cases can be made with greater reliability since the physical conditions are definitely reproducible.

(4) Setting up the patient is more simple and more definite, the conditions being the same for all cases of the same type.

The same kind of technique has been described by Lederman [30] for the treatment of carcinoma of the penis. This case, of course, is an easy one to deal with, but it exemplifies the advantages of the method very well.

11. Dosage Recording

The many physical factors that should be recorded in radium teletherapy have been indicated earlier in the chapter. A most convenient and significant method [16] of recording many of these factors is by means of a graph in which the number of days from the beginning of treatment are plotted as abscissæ, while the ordinates express the dosage in röntgens. Separate curves may be kept for the dosage received by the primary tumour, the glands and the skin. The increase in dosage may be seen from the graphs at a glance, as may be seen from Fig. 94, which shows a typical set of such curves for an actual case. A useful method of expressing the time spacing of dosage in such cases may possibly be in terms of the mean slope of the curves; the slopes would give some measure of the average rate of dosage for the whole period of treatment.

From data obtained at Westminster Hospital [31] and published by other institutions, the treatment period usually ranges from four to seven weeks, during which tumour doses of gamma radiation between 5,000 and 8,000 röntgens are given. Moist peeling of the skin appears to be produced in the same period by a total dose of 6,000–7,000 röntgens.

radium therapy, since treatment by radium is usually a very localised procedure, and the importance of homogeneity diminishes with the volume of the tissue irradiated.

"The sharply marked maximum, commonly known as the 'hot-spot' characterising a heterogeneous field, need not be the 'enfant terrible' of technique provided that it be controlled, that is, either directed into the tumour where it can do most good, or alternatively removed to a safe region where it can do least harm." Their paper illustrates a number of methods of obtaining this control.

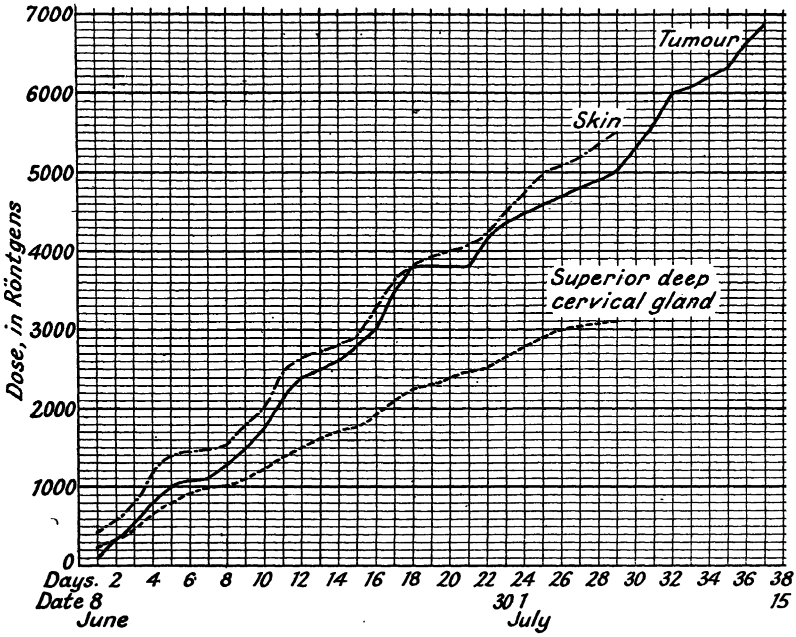

FIG. 94. Typical graphical records of dosage in treatment by teleradium.

12. Energy Absorption in Radium Teletherapy

An aspect of dosage that has hitherto received little consideration, but which has recently received attention, is that which concerns the total energy absorbed in the body as a whole. It would seem that the information now available on this subject, along with the further information that will no doubt be brought forward in the future, will prove useful in the further clinical consideration of patients receiving radio-therapy. It is likely, for example, that the changes produced within the tissues are not due solely to the energy directly absorbed by these tissues; they may also depend on the changes produced in neighbouring tissues which may have been affected by the radiation. Yet again, the constitutional effects of an intensive course of treatment by radiation are most obvious, and the increase of this general effect with the volume of tissue irradiated is well known; such phenomena are conceivably related to the total energy absorbed by the whole body during the treatment. Indeed, it could be suggested that attempts to correlate general blood changes with the radiation therapy, such as have been made,[31] might possibly lead to more valuable information if the data concerning the total energy absorbed could be made available.

We have seen (Chap. III) that the real energy conversion when a dose of one röntgen is delivered to 1 gram of air, is a close approximation to the energy absorbed in the same mass of tissue. It has been suggested,[32, 33] that this quantity be referred to as a "gram-röntgen." If dose is integrated throughout a given volume or mass, the energy absorbed will be determined in gram-röntgens; this quantity has been referred to as the integral dose.[33] In the case of a circular beam of gamma rays (or X-rays) it is possible to determine the integral dose by the use of the isodose surfaces of the beam since the volume of tissue between any two surfaces may be determined. The average dose may be determined for such volumes and by multiplication of the volume (or more strictly, the mass) and the average dose, the integral dose is obtained.[33] Methods of calculating the integral dose which may be applied to rectangular as well as circular fields have also been described.[34, 35, 36]

In practice one is usually concerned with a number of beams directed through varying thicknesses of tissue, and such conditions would have to be allowed for in a complete estimation of the total energy absorbed. As a beginning, however, it is of interest to examine the integral dose within an absorbing medium when a definite dose, say 100 röntgens, is measured at the surface to which the beam is applied. For comparative purposes we may follow Mayneord[33] and perform the integration down to the 10 per cent. isodose curve. The results of such determinations for the two beams of the Westminster Hospital 4-gram unit are given in Table 25 along with similar data that Mayneord[33] has given for two radium units used at the Royal Cancer Hospital.

TABLE 25.—"*Integral-doses*" *for Various Radium Mass Units*

Type of radium unit	Focus-skin distance	Diameter of field	Gram-röntgens to 10% dose contour
	cm.	cm.	
Westminster 4 gram unit .	8·0	3·5	12,160
Westminster 4 gram unit . .	8·0	9·0	77,418
Royal Cancer Hospital, 1 gram unit	5·0	5·0	14,593
Royal Cancer Hospital, 5 gram unit	8·2	8·0	51,587

A comparison of the integral doses for the two fields of the Westminster Hospital unit, in which all conditions except field size are identical, shows that their ratio is practically equal to the ratio of the respective areas of the fields. The integral dose should increase with increase of focus-skin distance, since all the depth doses will be increased. It is therefore interesting to note that the integral dose of the unit having only 5 cm. focus-skin distance, but a 5 cm. diameter field, is greater than that of the unit with 8 cm. focus-skin distance, but only 3·5 cm. diameter field. The size of field is obviously an important factor in determining the total energy absorbed.

Another approach to the problem of total energy absorption in beam therapy, that of direct measurement, has been indicated by Grimmett,[16] but unfortunately none of the results obtained by the method have been published. To make such measurements Grimmett has constructed a life-size model of a whole body in sheets of graphited celluloid with small air gaps between them. Alternate sheets are connected to a battery and the others to a galvanometer so that the ionization current developed in the air between the plates is measured. This current is proportional to the energy absorbed in the tissues, the thickness of the air gaps and celluloid sheets being such that the overall density of the model is unity. This method has the advantage that it records also the energy absorbed due to radiation well outside the beam itself. In radium beam therapy the amount of this "stray" radiation may be considerable, since it is not possible to provide perfect screening without making the dimensions of the radium container inconveniently large. We have endeavoured to estimate the order of magnitude of the radiation absorbed by the body outside the direct beam of the Westminster Hospital unit by assuming that the dosage curves measured for protection purposes (see Chap. VIII, Fig. 97, p. 204) will be approximately the same in the presence of the body. Thus, considering the beam applied to the neck of a patient, and making certain simplifying assumptions concerning the length, mass, shape, etc., of the body, it appears that the energy absorbed outside the beam may be more than one-half that absorbed in the direct beam of the 3·5 cm. diameter field.

Bush [37] has recently described a method and apparatus for determining the energy absorption during the teleradium treatment of patients and has given the results for a series of cases.

Similar questions of energy absorption arise in the other methods of radium therapy and in protection problems (see Chap. VIII), but as yet investigations of these questions have only been begun.

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CHAPTER VIII

PROTECTION

1. Recommendations for Protection

PROTECTION of radium workers has to be provided against beta and gamma radiation. The effects of beta radiation are mainly suffered by the hands, which may be in relatively close contact with radium sources. Gamma radiation can affect the whole body, the internal organs, vascular and reproduction systems. Recommendations for such protection, based upon experience and research of the previous years, have been drawn up by the British X-ray and Radium Protection Committee.[1] These are as follows :—

(A) RADIUM SALTS (BETA AND GAMMA RADIATION). (1) To protect the hands from beta rays, reliance should be placed, in the first instance, on distance. Radium should be manipulated with long-handled forceps and should be carried from place to place in long-handled boxes, lined on all sides with at least 1 cm. thickness of lead. All manipulations should be carried out as rapidly as possible. It is recommended that an examination of radium or radon operators' hands be made by a medical officer every three months.

(2) Radium, when not in use, should be stored in a safe as distant as possible from the personnel. It is recommended that the safe should be provided with a number of separate drawers individually protected (so that a minimum quantity of radium is exposed at any time when it may be withdrawn from or returned to the safe). The amount of protection should correspond to the values given in Table 26 (p. 197). These values, based on working conditions where there is proximity to radium, may be reduced for a larger working distance.

(3) A separate room should be provided for the " make-up " of screened tubes and applicators, and this room should be occupied only during such work. The room should be provided with an exhaust fan (to remove stray radon), the control switch for which should be outside the room.

(4) To protect the body from gamma rays during handling of

radium, a screen of not less than 2·5 cm. thickness of lead should be used, and proximity to the radium should occur only during actual work and for as short a time as possible.

(5) The measurement room should be a separate room, and it should preferably contain the radium only during its actual measurement.

(6) Radium containers should be tested periodically for leakage of radon, as quantities of radon may otherwise accumulate in radium safes containing leaky containers. Where possible, safes should be fitted with exhaust fans which should be operated for ten minutes before the safe is opened.

(7) Nurses and attendants should not remain in close proximity to patients undergoing radium treatment with quantities of radium exceeding 0·5 gram.

TABLE 26.

Maximum quantity of radium Element in grams	Thickness of lead in cm.
0·2	8·5
0·5	10·0
1·0	11·5
2·0	13·0
5·0	15·0
10·0	17·0

(8) All unskilled work, or work which can be learnt in a short period of time should preferably be carried out by temporary workers, who should be engaged on such work for periods not exceeding six months. This applies especially to nurses and those engaged in " making-up " applicators.

(9) Discretion should be exercised in transmitting salts by post.* In the case of small quantities (less than 10 mgm. of radium element) it is recommended that radium be enclosed in a container covered

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* During war time radium *may not* be transported through the medium of the Post Office. (See Ministry of Home Security's circular, October, 1941, on " Air raid precautions to be taken by holders and users of radium.")

with 3 mm. of lead, whereas for quantities between 10 and 50 mgm. of radium element, the container should be supported in the centre of a large box, *e.g.*, minimum dimensions 1 × 1 × 1 ft. Packages containing more than 50 mgm. of radium element are preferably sent by rail or hand under suitable conditions of protection. (From Fifth Edn., 1938.)

(10) (War-time ruling concerning transport.) Where radium must be conveyed, it should preferably be sent by messenger. In the case of small quantities of radium it is possible to adopt an alternative method of transport, namely, by passenger train. Information regarding the quantity of radium and the type of transport container which will be accepted for transmission by passenger train should be obtained from the Railway Companies.

(11) Chemical manipulations with radium should be carried out under the most rigid conditions of safety that can be devised, because in work of this kind there is danger of injury by alpha, beta and gamma rays. Work of this character is so varied that it is impossible to give specific recommendations.

The special precautions which must be observed by all of those engaged in luminising, *i.e.*, painting objects with a radioactive fluorescent mixture have been embodied in a brochure entitled "The Factories (Luminising) (Health and Safety Provisions) Order, 1942, made by the Ministry of Labour and National Service under Regulation 60 of the Defence (General) Regulations, 1939," published by H.M. Stationery Office.

(B) RADON (BETA AND GAMMA RADIATION). (12) The handling of radon should be carried out, as far as possible, during its relatively inactive state.

(13) The escape of radon should be guarded against very carefully: the room in which it is prepared should be provided with an exhaust fan, the control switch for which should be outside the room.

The radon of the air in laboratory, factory, workshop or other working quarters, should not exceed a concentration of 10^{-10} curie per litre.

If this concentration is found in the expired air from any operator a repeat test should be made after the person has remained away from work for forty-eight hours (*e.g.*, a week-end). Should radon then be found in a concentration of even 10^{-11} curie per litre it is presumptive evidence of radium in the body and the operator should at once discontinue such work.

(14) Where radon is likely to come into direct contact with the fingers, thin rubber gloves should be worn to avoid contamination of the hands with active deposit. Otherwise the measures recommended for radium salts should be carried out.

(15) The pumping room should preferably be contained in a separate building. The room should be provided with a connecting tube from a special room in which the radium is stored in solution. The radium in solution should be heavily screened to protect persons working in adjacent rooms. This is preferably done by placing the solution in a lead-lined enclosure, the thickness of lead being in accordance with Table 26.

(C) RADIUM TELETHERAPY (GAMMA RADIATION). (16) The risks to the operator attendant on the use of large quantities of radium in radium therapy may be largely obviated if some system of remote control is adopted by which the radium is only introduced into the container after the latter is adjusted on the patient. If such arrangements are not available, the importance of expeditious handling cannot be exaggerated.

Rooms used for radium teletherapy should be so equipped that adjacent rooms in permanent occupation are adequately protected.

(17) The thickness of lead required to secure a tolerance dosage-rate of 10^{-5} *r* per second at various distances from various quantities of radium element are given in Table 27.

TABLE 27

Quantity of radium in grams (0·5 mm. Pt. screen)	Thickness of lead in cm. to give tolerance dosage-rate at the following distances from radium source				Tolerance distance with no lead, in metres
	50 cm.	1 metre	2 metres	5 metres	
1	9·0	6·0	3·0	—	4·5
2	10·5	7·5	4·5	1·0	6·5
5	12·5	9·5	6·5	2·5	10·5
10	14·0	11·0	8·0	4·0	14·5

The known dangers to be guarded against are (1) injuries to superficial tissues and (2) changes in the blood and derangement of internal organs, particularly the generative organs. The evidence available at present suggests that under satisfactory working conditions, a person in normal health can tolerate a continuous irradiation from gamma rays during a working day of seven hours a day for five days a week at a dosage-rate of 10^{-5} r/sec., and the protective values given in Table 27 are generally in accord with this figure under average conditions.

Various apparatus, carriers, etc., that are used for the manipulation of radium while providing protection in accordance with the recommendations[3] are illustrated in Fig. 95.

2. Protection from Gamma Radiation

Because of the great penetrating power of gamma radiation and the increasing use of large quantities of radium (and super-voltage X-rays) the question of protection from gamma radiation is one which has received considerable attention. As already pointed out, the accepted tolerance dosage conditions (which are based essentially upon X-ray evidence) are a continuous exposure to gamma radiation throughout a working day at a dosage-rate of 10^{-5} r/sec., which corresponds to a daily dose of about 0·25 röntgens. In view of the different physical characteristics of gamma radiation and X-radiation, some workers feel that the figure is too high. Direct experiments recently made with rats by Russ and Scott[2] certainly suggest that the safe value is not likely to be any lower. Thus all protection measures are designed to ensure that the doses of gamma radiation received by personnel working with radium are not in excess of the tolerance amount.

The two essential methods of obtaining protection are (*a*) by suitable screening of the rays by dense materials and (*b*) by distance from the source of the rays. Usually combinations of both methods are used.

3. Protection afforded by Materials

(1) *Lead.* On account of its high density and comparative cheapness, the most commonly used protective material is lead. In the form of either sheets or small bricks it may be adapted to most purposes.

The data given for the protective properties of lead in the foregoing Recommendations are largely derived from the work of

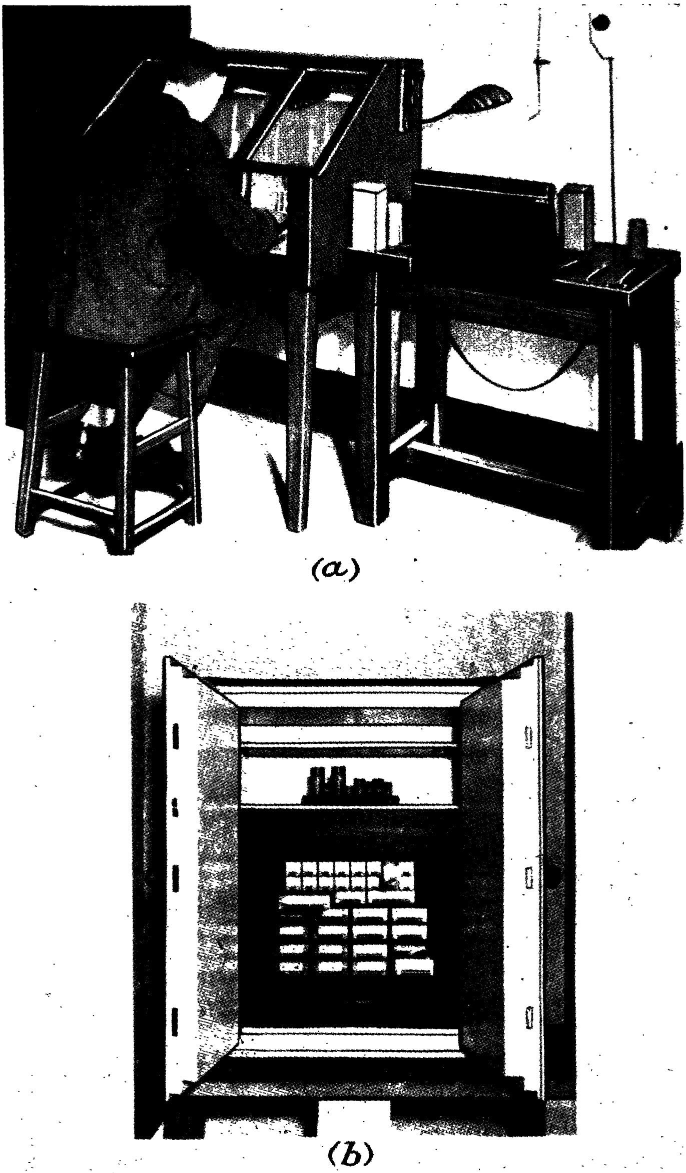
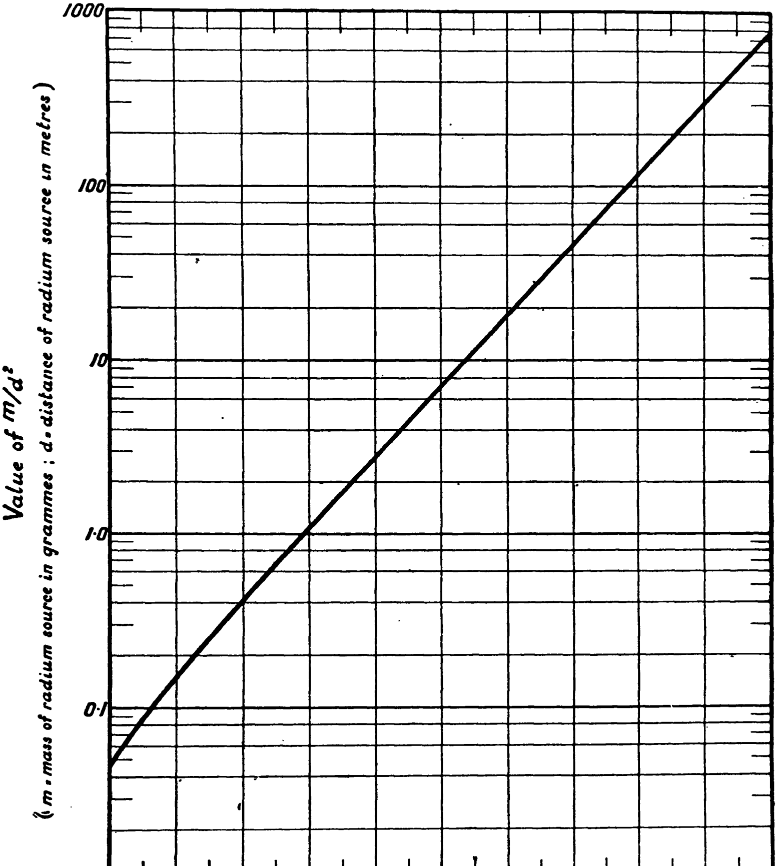


FIG. 95. Illustrating methods of providing gamma ray protection. (*Kaye, Binks and Bell.*)

(*a*) Shows two types of bench for the manipulation of radium sources, including forceps and lead carrier pots.

(*b*) Shows a radium safe with many drawers each protected individually.

Kaye, Binks and Bell[3] at the National Physical Laboratory, who based their results upon the assumption that the Sievert unit dose (1 Imc.) is equivalent to 8 röntgens per hour. It has been shown[3] that when lead screenage is added to a radium source filtered by 0·5 mm. platinum so as to completely surround the source, the transmission curve is virtually a straight line up to 20 cm. thickness of lead, which gives a linear absorption coefficient μ for the gamma radiation, equal to 0·5 cm.$^{-1}$ Using this result and the inverse



(Kaye, Binks and Bell.)

FIG. 96.

square law, a curve may be constructed[3] as shown in Fig. 96 from which may be read off the thickness of lead required to reduce the gamma radiation at a particular distance d metres from m grams of radium element to the tolerance dosage-rate. The curve expresses the required thickness in terms of m/d^2. Thus at 1 metre from 1 gram of radium element ($m/d^2 = 1{\cdot}0$); the required thickness is 5·8 cm.

(2) *Building Materials.* The protection against gamma radiation afforded by various building materials has also been examined,[4, 5] and some of the main findings are given in Table 28. This table shows the lead equivalents of various materials in respect of the absorption of gamma rays.

The information set out in Table 28 is valuable for the consideration and planning of departments designed for the practice of radium therapy, especially with mass units.

TABLE 28.—*Absorption of Gamma Rays in Various Materials—Lead Equivalents (Kaye, Bell and Binks*[4, 5]*)*

Material :	Iron	Barium concrete or plaster 2 parts coarse $BaSO_4$, 2 parts fine $BaSO_4$, 1 part cement, or 1 : 1 : 1 of same	Barium concrete or plaster 2 parts coarse $BaSO_4$, 2 parts sand, 1 part cement, or 1 : 1 : 1 of same	Concrete 2 parts ballast, 2 parts sand, 1 part cement	Brick (Danes-Hill red)	Brick (Yellow stock)	Coke breeze (clinker concrete)
Mean density :	7·9 gm./c.c.	3·2 gm./c.c.	2·7 gm./c.c.	2·2 gm./c.c.	1·9 gm./c.c.	1·6 gm./c.c.	1·2 gm./c.c.
Lead Equivalent mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.
1	2·5	5	7	8	11	15	16
2	5	10	13	16	20	27	30
3	7	15	18	22	28	39	43
4	8·5	19	24	29	37	50	55
6	12	28	34	40	50	70	75
8	16	36	45	55	65	85	95
10	19	45	55	65	80	105	115
15	27	65	75	90	110	150	165
20	35	85	95	120	150	200	220
50	80	200	225	280	—	—	—
100	150	400	450	550	—	—	—

4. Protection Afforded by Distance

Whenever one has to handle quantities of radium it should always be borne in mind that distance is the most economic, the most easily obtained and the most satisfactory form of protection. Doubling the distance, for example, is roughly equivalent to increasing the lead protection by nearly 3·0 cm.

Assuming the inverse square law, we may deduce a simple relation between the quantity of radium (assumed screened by 0·5 mm. Pt.) and the distance from it at which the dosage-rate falls to the tolerance value. Suppose we have m mgm. of radium element and we are concerned to know at what distance d cm. from this source, the dosage-rate falls to the tolerance value of 10^{-5} r/sec.

The intensity at the distance $d = \frac{m}{d^2}$ (Imc.) or, if 1 Imc. is taken as equivalent to 8·4 r/hr.

Then the dosage-rate at the distance $d = \frac{m}{d^2} \times 8{\cdot}4 \times \frac{1}{60} \times \frac{1}{60}\, r/\text{sec.} = 0{\cdot}00233\, \frac{m}{d^2}\, r/\text{sec.}$

This is to be equal to the tolerance value.

$$i.e.,\ 0{\cdot}00233\, \frac{m}{d^2} = 10^{-5}$$

$$\text{or } d = 15{\cdot}3\sqrt{m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

By means of equation (1) we may readily calculate the tolerance distance for any quantity of radium.

5. Investigation of the Adequacy of Protection Measures

The discussion of protection so far has dealt entirely with the measures that should be taken in order to ensure adequate protection against radium gamma radiation and with the premises upon which the measures are based. In recent years, especially with the advent of more large mass units, the physicist has tended to go further and to examine whether the measures, when taken, do provide adequate protection of the personnel under actual working conditions. These investigations have usually involved the study of (*a*) the amount of stray radiation that reaches various points in the neighbourhood of the radium and (*b*) the actual dose received by personnel concerned with the use of the radium.

(*a*) Radiation in the Neighbourhood of Radium. For investigations of this kind, because of the relatively low dosage-rates that have to be measured, it is necessary to use a very sensitive measuring system. The required sensitivity may be obtained quite readily by using a sufficiently large ionization chamber. Grimmett and Read [6] used a chamber having an air volume of 3·4 litres for an investigation of the stray radiation in the various rooms throughout a building in which was housed a 5-gram radium mass unit (Chap. VII, p. 168). They found that the dosage-rate recorded was everywhere less than 10^{-5} *r*/sec., except for a few places in the immediate vicinity of the treatment room where the unit was located.

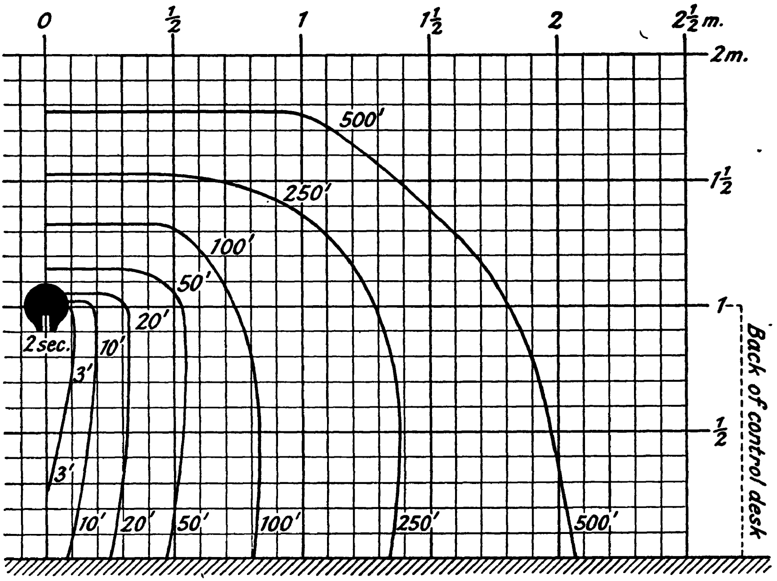


Fig. 97. Distribution of stray radiation around the Westminster Hospital 4-gram unit.

Flint and Wilson [7] published the results of measurements of the radiation immediately around the Westminster Hospital 4-gram unit (Chap. VII, p. 164). Some of their results are shown in Fig. 97. This shows the stray dosage around the unit in the form of isodose curves expressing the exposure required (in minutes) for the reception of a dose of 0·3 röntgens. It is seen that with the unit directed vertically downwards, the tolerance dosage-rate is exceeded only at distances less than 2 metres from the unit. At the rear of the unit, however, it is possible to approach to within about 70 cm. before the tolerance dosage-rate is reached. For this reason, all personnel connected with the use of the unit are instructed to keep "behind" the unit whenever possible. For making the measurements, a gold leaf electroscope with walls of a light atom material was used for the lowest dosage-rates and elektron metal condenser chambers were used for the higher dosage-rates. Similar results have been published by others[3] for a 1 gram radium source mounted in the form of a radium unit.

(*b*) MEASUREMENT OF DOSAGE RECEIVED BY PERSONNEL. The information obtained by such investigations as have been described above, serves as an extremely valuable guide to the degree of safety existing, but has not the same value as details of the actual dose received by the personnel. If the latter is known it may be seen at once whether the dosage received does or does not exceed the tolerance amount. In addition it would appear to be possible to correlate the dosage received, with the reaction of the individual over a period of time, as determined by means of the periodic blood counts that are carried out as routine. Thus it should be possible to judge the adequacy of the protection recommendations. This approach, in which the dosage received by personnel is directly measured, is furthermore, applicable to personnel engaged on all kinds of radium work such as the preparation of radon, construction of plaques, introduction of interstitial sources, etc. Such measurements are valuable in that they indicate any carelessness that may develop as a result of familiarity breeding contempt.

The Sievert condenser chamber technique is exactly what is needed for investigations of this kind since the chambers act as integrating dosemeters. Some workers use the photographic method which serves the purpose quite well,* but the condenser chamber is to be preferred, since the measurement may be made more directly. Measurements of this kind have been reported by Grimmett and Read[6] and by Wilson.[8] The condenser chambers used by these authors are illustrated in Fig. 45 (*a*) and (*b*) (p. 98). The chambers used by Wilson are not so robust as those of Grimmett and Read, but they have proved quite satisfactory in practice (some have been used continuously, day after day, for several years) and are considerably simpler to construct. The data obtained by these authors are of two different types.

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* The National Physical Laboratory has established a protection service by means of sensitive photographic films. Full details of this service are given in a Ministry of Health Circular 2718 dated November, 1942.

Grimmett and Read [6] were concerned with the dosage received by personnel who periodically transferred the whole of 5 grams of radium from a radium unit to a safe and *vice-versâ*. They wished to ensure that the rotation of the personnel performing these duties was such as to prevent any individual receiving excessive dosage. A typical record of the results obtained for one week is shown in Table 29. The time taken for the transference ranged between ten and twenty seconds and it was found that on an average, the dose received during a single transfer was of the order of 0·015 röntgens. For the most part, as can be seen from Table 29, the daily doses were considerably smaller than the tolerance amount.

TABLE 29.—*Analysis of Nurses' Exposure to Radiation during One Week (Grimmett and Read [6])*

Nurse	Date	Number of transfers	Dose for the day	Average dose per transfer	Total dose in one week
A ----	Feb. 4, 1935	3	0·057 r		
	5	6	0·117 r		
	7	2	0·036 r	0·018 r	0·282 r
	8	2	0·015 r		
	9	3	0·057 r		
Ba ----	Feb. 4	9	0·192 r		
	7	6	0·147 r	0·021 r	0·405 r
	8	4	0·066 r		
Be -----	Feb. 4	4	0·099 r	0·014 r	0·111 r
	5	4	0·012 r		
Ch ----	Feb. 5	8	0·087 r		
	6	12	0·162 r		
	7	4	0·096 r	0·015 r	0·555 r
	8	6	0·111 r		
	9	4	0·100 r		
Co -----	Feb. 4	4	0·063 r		
	5	4	0·051 r		
	6	2	0·060 r	0·021 r	0·354 r
	7	3	0·141 r		
	8	1	0·039 r		
M -----	Feb. 4	1	0·027 r	0·027 r	0·027 r
T -----	Feb. 4	4	0·108 r		
	5	4	0·183 r	0·036 r	0·291 r
W -----	Feb. 6	10	0·165 r		
	8	7	0·087 r	0·015 r	0·252 r

It is to be noted that in this case, the doses were received intermittently at moderately high dosage-rates (of the order of 5 *r*/hr. or less) in a short period of time.

The data obtained by Wilson [8] was of the dosage received by personnel working with the radium mass units at Westminster Hospital, that is, a record of the dosage received as stray radiation during the setting up of patients for treatment and other necessary operations. At no time, except by carelessness on the part of the operator such that he (or she) exposed himself to the direct beam of radiation, was this dosage received at even a moderate dosage-rate. Condenser ionization chambers were carried continuously by the personnel when on duty, and altogether, data was obtained for a period of three years, during which time, three different sets of conditions existed. These different conditions were due to modifications and additions to the quantity of radium in use. The results obtained are summarised in Table 30.

TABLE 30.—*Summary of Exposure of Workers to Gamma Rays over a period of Years* (*Wilson* [8])

Working conditions	Operator	Average daily dose	Period during which records were obtained
2 gram unit. Average screenage 5 cm. lead.	1. ------	0·205 r	7 months
	2. -------	0·253 r	2 months
	3. ------	0·249 r	1 month
	4. (Temporary)	0·251 r	1 month
4 gram unit. Average screenage 5 cm. Tungsten alloy, equivalent to 7·5 cm. lead approx.	1. ----------	0·150 r	13 months
	2. -----------	0·168 r	13 months
	3. ----------	0·215 r	13 months
	4. (Temporary)	0·188 r	2 months
Both the above units together	1. ---------	0·129 r	20 months
	2. ----------	0·135 r	20 months
	3. -------	01·18 r	20 months

In no case did the average daily dose seriously exceed the recommended tolerance amount. The marked improvement in protection in spite of the increase in the total quantity of radium is interesting; it is attributed to stricter rules for the personnel working with the radium and to the greater care exercised because of the quantities of radium in use. In actual practice, great care and common-sense, with a vigorous application of the inverse square law, goes far towards increasing protection.

All the above workers record[6, 8] that none of the personnel involved showed any ill effects that could be attributed to the radiation.

The method of directly measuring the dose received by the worker, will no doubt also furnish useful information concerning the doses received by surgeons in their interstitial work. Although the quantities of radium involved are much smaller, there is, nevertheless, a more intimate contact.

6. Protection and Total Energy Absorption

In the work referred to above, Grimmett and Read[6] discussed the fact that in the problem of protection we are concerned rather with the total energy absorbed than with the dosage at a particular point and with such ideas in mind Grimmett[9] has built a life-size model of the human body with celluloid plates and air spaces such that the overall density is unity. The model comprises a large ionization chamber such that the absorption of gamma ray energy in the whole body may be determined for any particular set of conditions, *e.g.*, for a patient undergoing treatment or for personnel giving the treatment. Actual results have not been published.

The same problem has recently received attention on theoretical lines from Mayneord.[10] He suggests that " the blood changes and general effects of the radiation would depend, not on the dose at a particular point, but on the total energy absorbed in the body as a whole and it is indeed a formal criticism which might be levelled at our present protection regulations that they pay no heed to the distinction between whether we are exposed to a needle beam of rays or to an atmosphere of radiation covering the whole body. Probably the latter is envisaged, but no explicit distinction is made." Mayneord[10] showed that the *energy flow* per röntgen of gamma radiation is nearly twice that for X-rays of wave-length 0·22 Angström units and the difference is even greater for X-rays of longer wave-length than this. Remembering that the " tolerance dose " was largely estimated from the biological effects of long wave-length X-rays, it would seem that the tolerance dose for gamma rays may be too high. There is insufficient evidence upon which to base any definite statement, but it is evident that much more investigation is needed on such questions as the quality of scattered radiation, integral dose and the distribution of radiation under tolerance conditions. It has been shown further[10] that the total of energy absorbed by an individual weighing 80 kgm. exposed for one year to a dosage-rate of 0·1 röntgen per diem (one half the tolerance amount) uniformly throughout, is equal to that delivered by 200 kv. X-rays applied to a 10 cm. diameter field for a total dose of 3,000 röntgens to the skin. One sees then, that the amounts of energy involved in protection are considerable, even when one also remembers the possibility of recovery of the organism because of the long period over which the delivery of the energy is spread.

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APPENDIX I

Table showing Decay of Radon and Equivalent Dose in mgm-hours.

THE following table gives the decay of radon with time, expressed as a percentage of the radon initially present. The last column gives the equivalent dosage per initial millicurie expressed in milligram-hours * (Eddy, C. E. and Oddie, T. H., Ref. 1, Chap. I).

Time		Percentage radon remaining	Equivalent mgm.-hours per initial millicurie
Days	Hours		
0	0	100·00	0·000
0	1	99·25	0·995
0	2	98·50	1·99
0	3	97·76	2·96
0	4	97·02	3·95
0	5	96·29	4·93
0	6	95·57	5·89
0	7	94·85	6·83
0	8	94·14	7·78
0	9	93·43	8·71
0	10	92·72	9·65
0	11	92·03	10·68
0	12	91·33	11·50
0	13	90·65	12·4
0	14	89·96	13·3
0	15	89·29	14·2
0	16	88·62	15·1
0	17	87·95	16·0
0	18	87·29	16·9
0	19	86·63	17·7
0	20	85·98	18·6
0	21	85·33	19·5
0	22	84·69	20·3
0	23	84·05	21·1
1	0	83·42	22·0
1	1	82·79	22·8
1	2	82·17	23·6
1	3	81·55	24·4
1	4	80·94	25·2
1	5	80·33	26·1
1	6	79·72	26·9

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* The author is indebted to the Department of Health, Commonwealth of Australia and to Dr. C. E. Eddy and Mr. T. H. Oddie for permission to reproduce this table from their booklet " Physical Aspects of Radium and Radon Therapy."

Time		Percentage radon remaining	Equivalent mgm.-hours per initial millicurie
Days	Hours		
1	7	79·12	27·6
1	8	78·53	28·4
1	9	77·94	29·2
1	10	77·35	30·1
1	11	76·77	30·8
1	12	76·19	31·5
1	13	75·62	32·2
1	14	75·05	33·0
1	15	74·48	33·8
1	16	73·92	34·6
1	17	73·36	35·3
1	18	72·81	36·0
1	19	72·26	36·7
1	20	71·72	37·5
1	21	71·18	38·2
1	22	70·64	38·9
1	23	70·11	39·6
2	0	69·58	40·3
2	1	69·06	41·0
2	2	68·54	41·6
2	3	68·03	42·4
2	4	67·51	43·1
2	6	66·50	44·5
2	8	65·50	45·8
2	10	64·52	47·1
2	12	63·55	48·4
2	14	62·60	49·6
2	16	61·66	50·9
2	18	60·74	52·1
2	20	59·83	53·2
2	22	58·93	54·4
3	0	58·05	55·6
3	3	56·75	57·2
3	6	55·47	59·1
3	9	54·23	60·9
3	12	53·02	62·4
3	15	51·83	64·0
3	18	50·67	65·5
3	21	49·53	67·0
4	0	48·42	68·5
4	3	47·34	70·0
4	6	46·28	71·2
4	9	45·24	72·5
4	12	44·22	73·8
4	15	43·23	75·1
4	18	42·26	76·3

Time		Percentage radon remaining	Equivalent mgm.-hours per initial millicurie
Days	Hours		
4	21	41·32	77·7
5	0	40·39	79·0
5	4	39·19	80·7
5	8	38·02	82·2
5	12	36·89	83·8
5	16	35·79	85·1
5	20	34·73	86·4
6	0	33·69	88·0
6	4	32·69	89·4
6	8	31·72	90·8
6	12	30·77	92·0
6	16	29·86	93·2
6	20	28·97	94·3
7	0	28·11	95·4
7	8	26·46	97·6
7	16	24·91	99·6
8	0	23·45	101·6
8	8	22·07	103·5
8	16	20·78	105·2
9	0	19·56	106·7
10	0	16·32	111·0
12	0	11·35	117·7
14	0	7·90	122·1
16	0	5·50	125·5
18	0	3·83	127·8
20	0	2·66	129·6
25	0	1·08	131·0
30	0	0·43	132·0
∞		0·00	132·5

APPENDIX II

A Table of some Integrals of the form:— $\int_0^\phi e^{-\frac{x}{\cos\phi}} . d\phi \; [x = \mu d]$

It has been seen in Chapter III that the calculation of dosage due to filtered line sources of radium involves the use of integrals of the form $\int_0^\phi e^{-\frac{x}{\cos\phi}} . d\phi$. Such integrals have been calculated graphically by Sievert.* Some of the most essential of these are tabulated below.†

ϕ	tan ϕ	$\int^\phi e^{-\frac{x}{\cos\phi}} . d\phi$								
		x								
		0·00	0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40
30°	0·577	0·524	0·497	0·471	0·447	0·424	0·402	0·382	0·364	0·345
31°	0·601	0·541	0·513	0·486	0·462	0·438	0·416	0·394	0·375	0·356
32°	0·625	0·559	0·530	0·502	0·476	0·452	0·429	0·406	0·387	0·367
33°	0·649	0·576	0·546	0·517	0·491	0·465	0·443	0·419	0·398	0·377
34°	0·675	0·594	0·563	0·533	0·505	0·479	0·456	0·431	0·410	0·388
35°	0·700	0·611	0·579	0·548	0·520	0·493	0·470	0·443	0·421	0·399
36°	0·727	0·628	0·595	0·564	0·535	0·507	0·483	0·455	0·433	0·410
37°	0·754	0·646	0·612	0·579	0·549	0·520	0·496	0·468	0·444	0·420
38°	0·781	0·663	0·628	0·595	0·564	0·534	0·508	0·480	0·456	0·431
39°	0·810	0·681	0·645	0·610	0·578	0·547	0·521	0·492	0·467	0·441
40°	0·839	0·698	0·661	0·626	0·593	0·561	0·534	0·504	0·478	0·452
41°	0·869	0·715	0·677	0·641	0·607	0·574	0·546	0·515	0·488	0·462
42°	0·900	0·733	0·694	0·656	0·621	0·587	0·559	0·527	0·499	0·472
43°	0·933	0·750	0·710	0·672	0·636	0·601	0·571	0·538	0·509	0·482.
44°	0·966	0·768	0·726	0·687	0·650	0·614	0·584	0·550	0·520	0·492
45°	1·000	0·785	0·743	0·702	0·664	0·627	0·596	0·561	0·530	0·502
46°	1·036	0·803	0·759	0·717	0·678	0·640	0·608	0·572	0·540	0·512
47°	1·072	0·820	0·775	0·732	0·692	0·653	0·620	0·583	0·550	0·521
48°	1·111	0·838	0·792	0·747	0·706	0·667	0·632	0·595	0·560	0·531
49°	1·150	0·855	0·808	0·762	0·720	0·680	0·644	0·606	0·570	0·540
50°	1·192	0·873	0·824	0·777	0·734	0·693	0·656	0·617	0·580	0·550
51°	1·235	0·890	0·840	0·792	0·748	0·706	0·668	0·628	0·590	0·559
52°	1·280	0·908	0·856	0·807	0·761	0·718	0·679	0·638	0·600	0·568
53°	1·327	0·925	0·872	0·821	0·775	0·731	0·691	0·649	0·611	0·577
54°	1·376	0·943	0·888	0·836	0·788	0·743	0·702	0·659	0·621	0·586
55°	1·428	0·960	0·904	0·851	0·802	0·756	0·714	0·670	0·631	0·595
56°	1·483	0·977	0·920	0·865	0·815	0·768	0·725	0·680	0·640	0·603
57°	1·540	0·955	0·936	0·880	0·829	0·780	0·736	0·690	0·649	0·612

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* Sievert R.M. Acta Radiol. Supplementum XIV. 1932.

† The author is indebted to the Editors of *Acta Radiologica* for permission to publish this table.

ϕ	tan ϕ	$\int_0^{\phi} e^{-\frac{x}{\cos\phi}}.d\phi$								
		x								
		0·00	0·05	0·10	0.15	0·20	0·25	0·30	0·35	0·40
58°	1·600	1·012	0·952	0·894	0·842	0·792	0·747	0·700	0·658	0·620
59°	1·664	1·030	0·968	0·909	0·856	0·804	0·758	0·710	0·667	0·629
60°	1·732	1·047	0·984	0·923	0·869	0·816	0·769	0·720	0·676	0·637
61°	1·804	1·064	1·000	0·937	0·882	0·827	0·779	0·729	0·687	0·644
62°	1·881	1·082	1·015	0·951	0·894	0·839	0·789	0·738	0·694	0·652
63°	1·963	1·099	1·031	0·965	0·907	0·850	0·799	0·747	0·702	0·659
64°	2·050	1·117	1·046	0·979	0·920	0·862	0·809	0·756	0·709	0·667
65°	2·145	1·134	1·062	0·993	0·932	0·873	0·819	0·765	0·717	0·674
66°	2·246	1·152	1·077	1·006	0·944	0·883	0·828	0·773	0·725	0·680
67°	2·356	1·169	1·093	1·020	0·955	0·893	0·837	0·781	0·733	0·686
68°	2·475	1·187	1·108	1·033	0·967	0·904	0·847	0·789	0·740	0·692
69°	2·605	1·204	1·123	1·047	0·978	0·914	0·856	0·797	0·746	0·698
70°	2·748	1·222	1·138	1·060	0·990	0·924	0·865	0·805	0·752	0·704
71°	2·904	1·239	1·153	1·073	1·001	0·933	0·873	0·812	0·758	0·709
72°	3·078	1·257	1·168	1·085	1·012	0·942	0·881	0·819	0·764	0·714
73°	3·271	1·274	1·183	1·098	1·022	0·951	0·889	0·826	0·769	0·719
74°	3·487	1·292	1·198	1·110	1·033	0·960	0·896	0·833	0·774	0·723
75°	3·732	1·309	1·213	1·123	1·044	0·969	0·903	0·838	0·779	0·727
76°	4·011	1·326	1·227	1·134	1·053	0·977	0·909	0·844	0·783	0·731
77°	4·332	1·344	1·241	1·145	1·063	0·984	0·916	0·850	0·787	0·734
78°	4·705	1·361	1·254	1·156	1·071	0·992	0·922	0·854	0·791	0·737
79°	5·145	1·379	1·268	1·167	1·080	0·998	0·926	0·858	0·794	0·739
80°	5·671	1·396	1·282	1·178	1·087	1·004	0·931	0·861	0·797	0·741
81°	6·314	1·414	1·295	1·188	1·095	1·010	0·935	0·864	0·799	0·743
82°	7·115	1·431	1·308	1·197	1·101	1·014	0·938	0·866	0·801	0·744
83°	8·144	1·449	1·319	1·205	1·107	1·019	0·941	0·868	0·802	0·745
84°	9·514	1·467	1·330	1·212	1·111	1·022	0·943	0·869	0·802	0·745
85°	11·430	1·484	1·341	1·217	1·114	1·024	0·944	0·870	0·802	0·745
86°	14·301	1·502	1·350	1·222	1·117	1·025	0·945	0·871	0·802	0·745
87°	19·081	1·519	1·358	1·225	1·119	1·025	0·945	0·871	0·802	0·745
88°	28·636	1·537	1·364	1·227	1·120	1·025	0·945	0·871	0·802	0·745
89°	57·290	1·554	1·367	1·227	1·120	1·025	0·945	0·871	0·802	0·745
90°	∞	1·572	1·367	1·227	1·120	1·025	0·945	0·871	0·802	0·745

APPENDIX III

Inverse Square Law Table

It has been seen in Chapter III that it is often possible to treat a radium source as approximately a point source or as a number of point sources placed according to the real shape of the source. To facilitate such calculation, Mayneord [*] has published a table giving the dosage-rates in röntgens per hour for point sources filtered by 0·5 mm. Pt. and having radium contents of 0·5, 1·0, 2·0, 3·0, 5·0, 10·0, 25·0 mgm. at distances from 0·1 cm. to 20 cm. The following table is an abridged form of the original and covers those ranges of values thought to be most frequently required in practice.[†]

The data are based upon a value of 8·3 röntgens per hour for the dosage-rate at 1 cm. from a point source of 1 mgm. of radium element enclosed in a platinum filter 0·5 mm. thick. If the filtration is other than 0·5 mm. platinum the values given in the table must be multiplied by the ratio of the appropriate factor (given below) to the standard 8·3.

Filter in mm. platinum	Conversion factor	Ratio
0·5	8·3	1·00
0·6	8·2	0·98
0·7	8·1	0·97
0·8	7·9	0·95
0·9	7·8	0·94
1·0	7·7	0·92
1·5	7·2	0·86
2·0	6·7	0·81

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[*] Mayneord, W. V. Inverse Square Law Table. Percy Lund, Humphries & Co. Ltd., London, June, 1938.

[†] The author is indebted to Professor W. V. Mayneord and the Governors of The Royal Cancer Hospital (Free) for permission to reproduce this data.

Distance in cm.	Dosage Rate in r/hr for Source						
	0·5 mgm.	1·0 mgm.	2·0 mgm.	3·0 mgm.	5·0 mgm.	10·0 mgm.	25·0 mgm.
0·100	415·0	830·0	1660	2490	4150	8300	—
0·125	265·6	531·2	1062	1594	2656	5312	—
0·150	184·4	368·9	738	1107	1844	3689	9222
0·175	135·5	271·0	542	813	1355	2710	6776
0·200	103·8	207·5	415	622	1038	2075	5188
0·225	82·0	164·0	328	492	820	1640	4099
0·250	66·4	132·8	265·6	398	664	1328	3320
0·275	54·9	109·8	219·5	329	549	1098	2744
0·300	46·1	92·2	184·4	277	461	922	2306
0·325	39·3	78·6	157·2	236	393	786	1964
0·350	33·9	67·8	135·5	203	339	678	1694
0·375	29·5	59·0	118·0	177	295	590	1476
0·400	25·9	51·9	103·8	156	259	519	1297
0·425	23·0	46·0	91·9	138	230	460	1149
0·450	20·5	41·0	82·0	123	205	410	1025
0·475	18·4	36·8	73·6	110	184	368	920
0·500	16·60	33·2	66·4	99·6	166·0	332	830
0·525	15·06	30·1	60·2	90·3	150·6	301	753
0·550	13·72	27·4	54·9	82·3	137·2	274	686
0·575	12·55	25·1	50·2	75·3	125·5	251	502
0·600	11·53	23·1	46·1	69·2	115·3	231	461
0·625	10·62	21·2	42·5	63·7	106·2	212	531
0·650	9·82	19·6	39·3	58·9	98·2	196	491
0·675	9·11	18·2	36·4	54·7	91·1	182	455
0·700	8·47	16·9	33·9	50·8	84·7	169	423
0·750	7·38	14·76	29·5	44·3	73·8	147·6	369
0·800	6·48	12·97	25·9	38·9	64·8	129·7	324
0·850	5·74	11·49	23·0	34·5	57·4	114·9	287
0·900	5·12	10·25	20·5	30·7	51·2	102·5	256
0·950	4·60	9·20	18·4	27·6	46·0	92·0	230
1·00	4·15	8·30	16·60	24·9	41·5	83·0	207·5
1·10	3·43	6·86	13·72	20·6	34·3	68·6	171·5
1·20	2·88	5·76	11·53	17·3	28·8	57·6	144·1
1·30	2·46	4·91	9·82	14·7	24·6	49·1	122·8
1·40	2·12	4·23	8·47	12·7	21·2	42·3	105·9
1·50	1·84	3·69	7·38	11·07	18·4	36·9	92·2
1·60	1·62	3·24	6·48	9·73	16·2	32·4	81·1
1·70	1·44	2·87	5·74	8·62	14·4	28·7	71·8
1·80	1·28	2·56	5·12	7·69	12·8	25·6	64·0
1·90	1·15	2·30	4·60	6·90	11·5	23·0	57·5
2·00	1·04	2·08	4·15	6·22	10·38	20·75	51·9
2·20	0·857	1·72	3·43	5·14	8·57	17·15	42·9
2·40	0·720	1·44	2·88	4·32	7·20	14·41	36·0
2·60	0·614	1·23	2·46	3·68	6·14	12·28	30·7
2·80	0·529	1·06	2·12	3·18	5·29	10·59	26·5
3·00	0·461	0·922	1·84	2·77	4·61	9·22	23·1
3·20	0·405	0·811	1·62	2·43	4·05	8·11	20·3
3·40	0·359	0·718	1·44	2·15	3·59	7·18	17·9
3·60	0·320	0·640	1·28	1·92	3·20	6·40	16·0
3·80	0·287	0·575	1·15	1·72	2·87	5·75	14·4
4·00	0·259	0·519	1·04	1·56	2·59	5·19	12·97
4·50	0·205	0·410	0·820	1·23	2·05	4·10	10·25
5·00	0·166	0·332	0·664	0·996	1·66	3·32	8·30
5·50	0·137	0·274	0·549	0·823	1·37	2·74	6·86
6·00	0·115	0·231	0·461	0·692	1·15	2·31	5·76
6·50	0·098	0·196	0·393	0·589	0·982	1·96	4·91
7·00	0·085	0·169	0·339	0·508	0·847	1·69	4·23

APPENDIX III

Distance in cm.	Dosage Rate in r/hr for Source						
	0·5 mgm.	1·0 mgm.	2·0 mgm.	3·0 mgm.	5·0 mgm.	10·0 mgm.	25·0 mgm.
8·00	0·065	0·130	0·259	0·389	0·648	1·30	3·24
9·00	0·051	0·102	0·205	0·307	0·512	1·03	2·56
10·00	0·042	0·083	0·166	0·249	0·415	0·830	2·08
11·00	0·034	0·069	0·137	0·206	0·343	0·686	1·72
12·00	0·029	0·058	0·115	0·173	0·288	0·576	1·44
13·0	0·025	0·049	0·098	0·147	0·246	0·491	1·23
14·0	0·021	0·042	0·085	0·127	0·212	0·423	1·06
15·0	0·018	0·037	0·074	0·111	0·184	0·369	0·922
16·0	0·016	0·032	0·065	0·097	0·162	0·324	0·811
17·0	0·014	0·029	0·057	0·086	0·144	0·287	0·718
18·0	0·013	0·026	0·051	0·077	0·128	0·256	0·640
19·0	0·011	0·023	0·046	0·069	0·115	0·230	0·575

APPENDIX IV

In the calculation of areas and volumes of triangular shape for surface and interstitial work, the following formulæ* are of value :—

(*a*) Area S of a triangle with sides of length a, b and c cm. (Fig. (i))

$$S = \tfrac{1}{4}.\sqrt{(a^2 + b^2 + c^2)^2 - 2\,(a^4 + b^4 + c^4)}\ .\text{sq. cm.} \quad (1)$$

When $a = b = c$, this becomes :—

$$S = 0{\cdot}433\, a^2 \text{ sq. cm.} \quad (2)$$

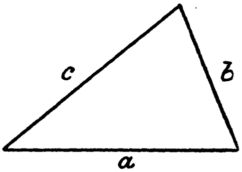

Fig. (i)

(*b*) Volume V of a prism of length L cm. and triangular section with sides a, b and c cm. :—

$$V = \text{A.L. c.c.} \quad (3)$$

where A is obtained from (1) or (2) above.

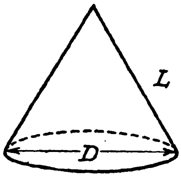

Fig. (ii)

(*c*) Volume V of a cone, with diameter of base D cm. and length of sloping sides L cm. (Fig. (ii)) :—

$$V = 0{\cdot}131\, D^2 \sqrt{4L^2 - D^2}\ \text{c.c.} \quad (4)$$

(*d*) Volume V of a pyramid, with sides of square base a cm. and length of sloping edges L cm. (Fig. (iii)) :—

$$V = 0{\cdot}236\, a^2 \sqrt{2L^2 - a^2}.\ \text{c.c.} \quad (5)$$

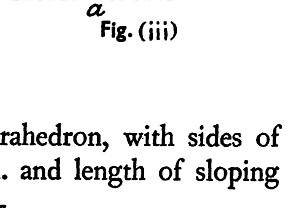

Fig. (iii)

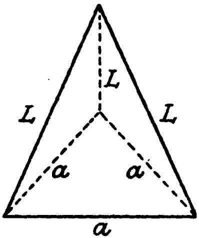

Fig. (iv)

(*e*) Volume V of a tetrahedron, with sides of triangular base each a cm. and length of sloping edges L cm. (Fig. (iv)) :—

$$V = 0{\cdot}0833\, a^2\sqrt{3L^2 - a^2}\ \text{c.c.} \quad (6)$$

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* Oddie, T. H. *Brit. Journ. Rad.* Vol. 12, 1940, p. 389.

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